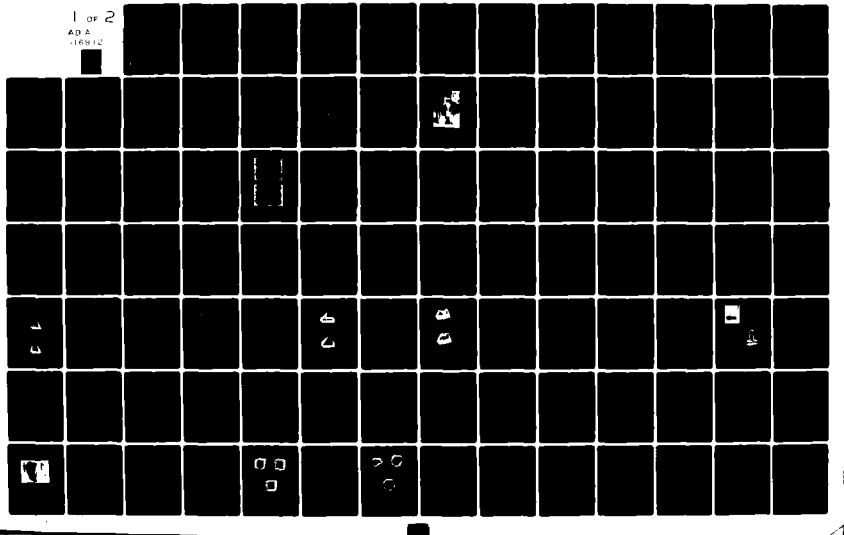
AD-A116 912 MASSACHUSETTS INST OF TECH CAMBRIDGE MAN-MACHINE SYS--ETC F/G 17/8
COMPUTER GRAPHIC REPRESENTATION OF REMOTE ENVIRONMENT USING POS--ETC(U)
AUG 81 D C FYLER N00014-77-C-0256

UNCLASSIFIED NL



(12)

COMPUTER GRAPHIC REPRESENTATION OF REMOTE ENVIRONMENT USING POSITION TACTILE SENSORS

DONALD CHARLES FYLER

AUGUST 1981

Contract N00014-77-C-0256
Engineering Psychology Programs
Office of Naval Research
Arlington, VA 22217

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE	READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO. AD-A116 912 / 3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) COMPUTER GRAPHIC REPRESENTATION OF REMOTE ENVIRONMENTS USING POSITION TACTILE SENSORS	5. TYPE OF REPORT & PERIOD COVERED
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) DONALD CHARLES FYLER	8. CONTRACT OR GRANT NUMBER(s) N00014-77-C-0256
9. PERFORMING ORGANIZATION NAME AND ADDRESS Massachusetts Institute of Technology 77 Massachusetts Avenue Cambridge, MA 02139	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS NR196-152
11. CONTROLLING OFFICE NAME AND ADDRESS Engineering Psychology Programs Office of Naval Research Arlington, VA 22217	12. REPORT DATE August 4, 1981
	13. NUMBER OF PAGES 129
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) Same	15. SECURITY CLASS. (of this report) UNCLASSIFIED
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

—

18. SUPPLEMENTARY NOTES

NONE

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Graphic Simulation	Simulated Environment	Teleoperators
2-D Depth Indicators	Man-Machine Systems	Clusting
Manipulators	Tactile Sensors	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The usefulness of remotely controlled manipulators is increasing as the need grows to accomplish complex tasks in hazerdous environments such as the deep ocean.

The best sensory input currently available to the operator of a remote supervisory controlled manipulator is a television picture of the manipulator and its surroundings. Very often, though, optical opacity due to suspended particles in the water can make television impractical or impossible to use.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE S/N 0102-LF-014-6601

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20. Abstract (continued)

This report investigates the use of touch sensors to construct a picture of the manipulator surroundings. One method studied was to find 3-dimensional surface points and show them on a computer graphic display. An extension of this was to reconstruct the surface of these points with the aid of a computer.

It was found to be possible to quickly construct a reasonable picture with a position touch sensor by showing 3-D surface points on the graphic display and then having them rotate about an arbitrary center. A better picture could be made by reconstructing the actual surface, but this took more computer time.

An informal evaluation by observers suggests that this method offers practical advantages for "seeing" objects in environments where vision is impossible.

COMPUTER GRAPHIC REPRESENTATION OF REMOTE ENVIRONMENTS USING POSITION TACTILE SENSORS

by

DONALD CHARLES FYLER

B.S.M.E., University of Massachusetts, Amherst
(1978)

SUBMITTED TO THE DEPARTMENT OF
MECHANICAL ENGINEERING IN PARTIAL
FULFILLMENT OF THE
REQUIREMENTS FOR THE
DEGREE OF

MASTER OF SCIENCE

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

August 1981

Signature of Author Donald Charles Fyler
Department of Mechanical Engineering
August 4,1981

Certified by Thomas B. Sheridan
Thomas B. Sheridan
Thesis Supervisor

Accepted by _____
W. M. Rohsenow
Chairman, Department Committee

COMPUTER GRAPHIC REPRESENTATION OF REMOTE ENVIRONMENTS USING POSITION TACTILE SENSORS

by

DONALD CHARLES FYLER

Submitted to the Department of Mechanical Engineering on August 4, 1981 in partial fulfillment of the requirements for the Degree of Masters of Science in Mechanical Engineering

ABSTRACT

The usefulness of remotely controlled manipulators is increasing as the need grows to accomplish complex tasks in hazardous environments such as the deep ocean.

The best sensory input currently available to the operator of a remote supervisory controlled manipulator is a television picture of the manipulator and its surroundings. Very often optical opacity due to suspended particles in the water can make television impractical or impossible to use. This report investigates the use of touch sensors to construct a picture of the manipulator surroundings. One method studied was to find 3-dimensional surface points and show them on a computer graphic display. An extension of this was to reconstruct the surface of these points with the aid of a computer.

It was found to be possible to quickly construct a reasonable picture with a position touch sensor by showing 3-D surface points on the graphic display and then having them rotate about an arbitrary center. A better picture could be made by reconstructing the actual surface, but this took more computer time.

An informal evaluation by observers suggests that this method offers practical advantages for "seeing" objects in environments where vision is impossible.

Thesis Supervisor: Thomas B. Sheridan
Title: Professor of Mechanical Engineering

ACKNOWLEDGEMENTS

I would like to thank Professor Thomas Sheridan for his support and for the opportunity to work in the Man-Machine Systems Laboratory. Special thanks to Calvin Winey for advice and help in maintaining lab equipment. His research in the field of manipulator simulation provided a basis for much of this report. I would like to thank Ahmet Buharali and Dana Yoeger for support of the computer system and for the help in understanding how it worked. I would also like to thank Ryang Lee for his help proof-reading and organizing this report. Finally I wish to thank all the Man-Machine Systems Lab members for making it an enjoyable place to work.

This research was supported in part by Contract N00014-77-C-256 with the Office of Naval Research. Arlington VA 22217. G. Malecki was contract monitor.

TABLE OF CONTENT

LIST OF FIGURES

CHAPTER 1. INTRODUCTION

Remotely controlled manipulators make it possible to perform tasks in hostile environments that would be impossible or very dangerous for humans to perform. It is very difficult and expensive to send a man down into the deep ocean to do a task. But tasks such as exploration, salvage, and maintenance of oil rigs must be done. Because the technology is not yet available to make a completely autonomous robot, some compromises must be made. A robot can be made as self sufficient as the technology allows and the higher order thinking can be left to a human controller. This robot-human system is called Supervisory Control and is meant to relieve the human of as much direct control as possible to minimize the amount of required transmitted data and perhaps even allow the robot to continue working during breaks in transmission.

In human-manipulator control systems, it is very important that the human have as much feedback as possible about what is happening at the manipulator. Sight is considered to be the most important source of feedback because it can be readily understood by the operator. If the operator cannot directly see the manipulator and manipulated object, (which is often the case), some sort of artificial vision must be provided. This is most often a television picture of the manipulator work area. Television

provides the best picture available but there are some problems that can make television hard to work with. Some of these problems are:

1) Television cannot give a reliable sense of depth because it is only displayed on a 2-dimensional screen. This can slow the operator's reaction time because he can never be sure if the manipulator arm or its surroundings are really in the place he thinks they are. It is possible to use two cameras to get a stereo picture but this kind of display requires undivided attention and the operator can become fatigued very quickly.

2) The raster picture on the television screen requires a massive data flow rate to refresh the screen in a reasonable amount of time. If the operator is trying to control a manipulator working on the bottom of the ocean or in deep space, the data flow rate can be very restricted by transmission problems. This means the operator will have to live with a fuzzy picture or a slow frame rate or both.

3) A television camera must have a clear view of the manipulator. It cannot see anything in turbid water and the television must always be located so obstructions do not block the view.

4) In modern types of supervisory control systems, a computer works intimately with the operator to control the manipulator. The computer should have as much feedback as possible made available to it. While a television picture is easily understood by a human, it is meaningless to a computer unless it has extensive, time-consuming processing. A computer of any control system is essentially blind to a television picture.

These problems show the need for investigating new, types of viewing systems for use in supervisory control. A system using touch sensors to construct a simulation of the surroundings of a manipulator is investigated in this report. This kind of simulation can be used to draw a picture to be viewed by a human or can be used to provide 3-dimensional information to a computer about the surroundings of the manipulator.

CHAPTER 2. PROPOSED SOLUTION

2.1 Constuction of a Picture with Touch Sensors

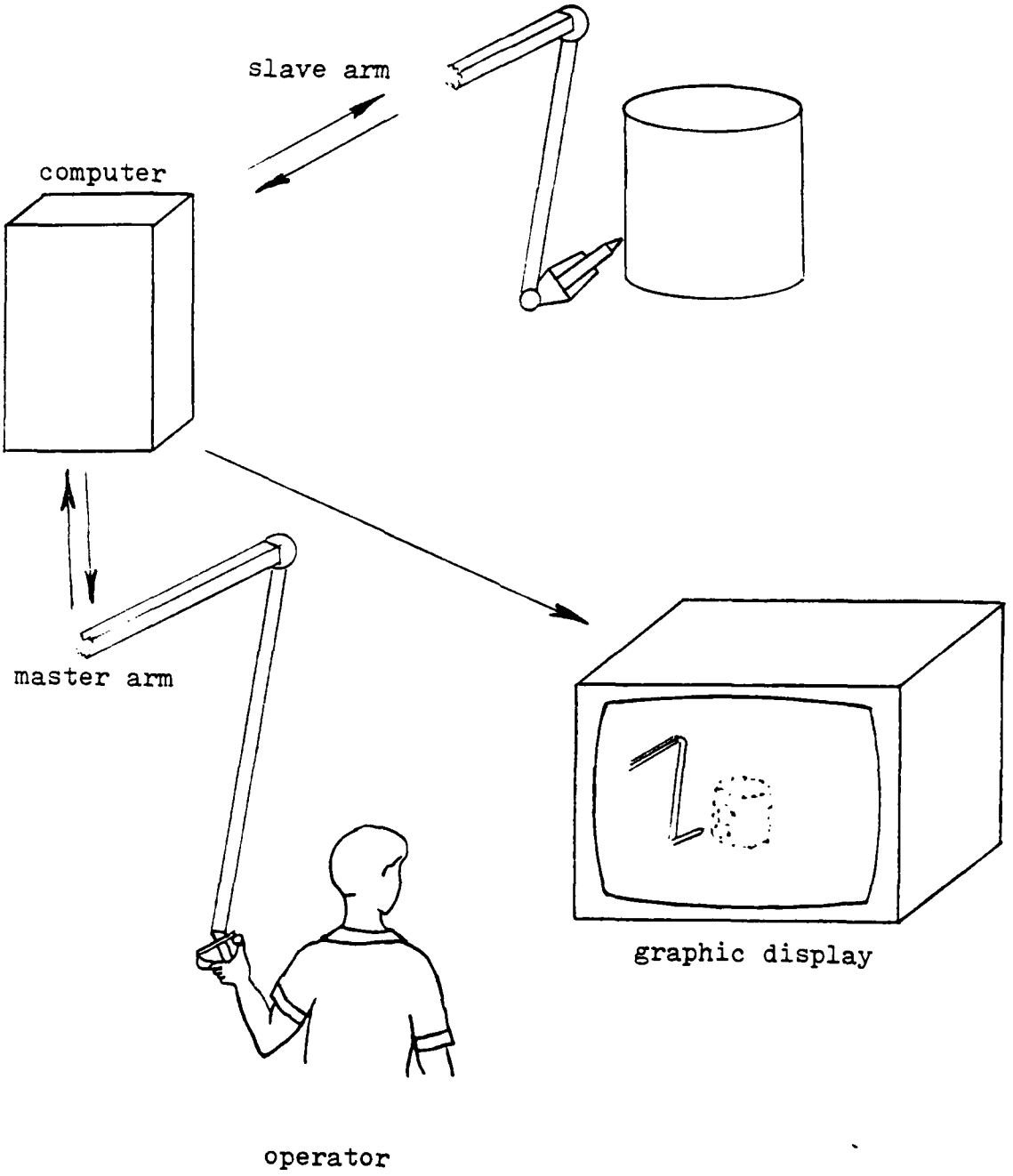
A method is needed to improve visual feedback using touch sensors for a human operating a remote supervisory controlled manipulator. One way is to find the coordinates of a large number of points on all the solid surfaces within reach of the manipulator. A picture of the manipulator surroundings can then be constructed with computer graphics by drawing a dot at each location where a solid surface is hit.

Points and their coordinates can be found by using touch sensors mounted on the manipulator. Whenever a sensor comes in contact with a surface it could send a signal to the computer to record the coordinates of the point touched. The computer can accurately calculate point coordinates if it is given the exact angles of the manipulator joints the instant the sensor is tripped, see Fig. 2.1.

A dynamic simulation of the manipulator itself can also be added to the display as a reference if these angles are known, [1]. This means an entire picture of the of the manipulator surroundings plus a moving picture of the manipulator can be made with just information on the values of the joint angles and indications of when sensors are tripped.

Very little transmitted data is required to describe

Fig. 2.1 Position Touch Sensors Used for Graphic Display



3-dimensional points as opposed to a television picture. Assuming the joint angles are to be transmitted anyway, all that is needed to describe a dot is an indication of which touch sensor had just been triggered. Its coordinates can then be calculated from the joint angles given at that instant.

A picture on a 3-dimensional graphic display has the same disadvantage as a television picture in that it can only be shown on a 2-dimensional screen. But a graphic display picture can be viewed from any angle, something a television cannot do without having the camera moved. An obstacle blocking a clear view of the manipulator on the display could be ignored by simply looking around it.

Also, because the data of the graphic display picture is stored in three dimensions, the picture can be modified to bring out it's depth of field. Showing shadows, orthographic views, and perspective will bring out three dimensionality, [1]. Dynamic pictures also bring out depth. The three dimensions of the picture become very apparent when it is slowly rotating on the screen.

An advantage of having the surroundings of the manipulator mapped out as discrete points is that it can be quickly interpreted by a computer. Say a task given to a computer is to move a manipulator arm from one spot to another without hitting any obstacles. If the computer is given enough information about 3-D point locations on the

obstacles, then it could be programmed to keep the the manipulator away from the surface points. This would be easier for the computer to solve than trying to interpret a flat television picture.

2.2 Construction of a Surface From Points

A problem with surface points shown on a graphic display is that they give a somewhat ambiguous indication as to what the surface is like between them. Without the surface, there is no way to calculate volume, surface area, or decide when something should be hidden from view.

A method was found to reconstruct the surface described by a given set of points with the aid of a computer. This method will be covered in some detail, as it provides a solution to the above problems and also can significantly improve the quality of the graphic display used in supervisory control.

Computer graphics can never replace television as a sense of sight in supervisory control but it could be a very useful aid to television or even an alternative in situations where television is impossible to use.

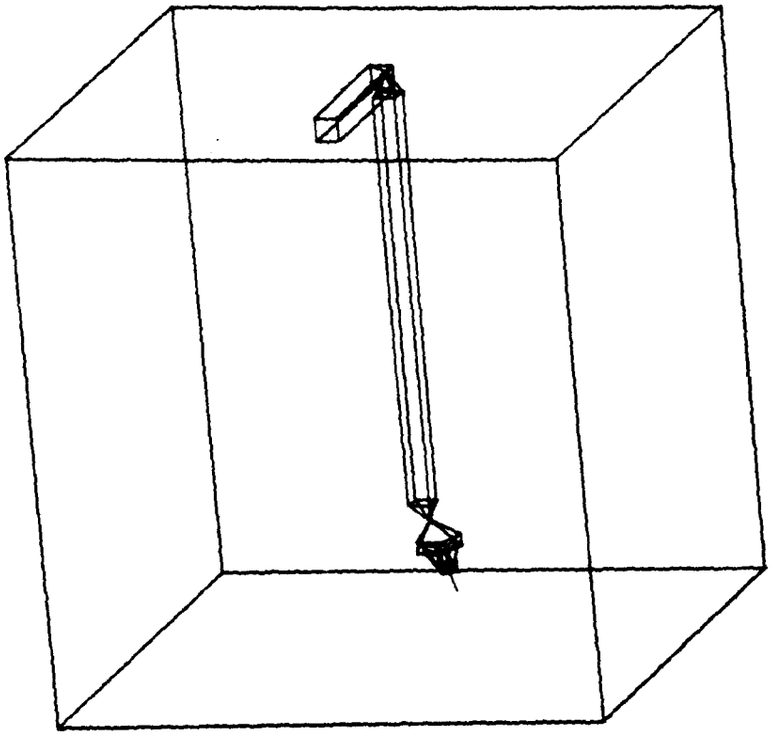


Fig 2.2 Vector Graphic Display of Manipulator

CHAPTER 3. EQUIPMENT

3.1 Manipulator

The manipulator used in this project was a master-slave E-2 built by the Argonne National Laboratories for use in radioactive environments, see Fig. 3.1. The control system used in experiments was analog with full force feedback. Control potentiometers installed at the servos provided a signal for determining manipulator joint angles. Interfaces between the manipulator and the A/D converter were installed by K. Tani [2].

3.2 Computer

A PDP 11/34 with a RSX-11M timesharing operating system was used for all computation. There was a FP11-A floating point processor installed to speed the fractional multiplication and division required for real time graphic transformations and simulation.

3.3 Vector Graphic System

All vector graphics were done on a Megatek 7000 System. It had a resolution of 4096 x 4096 on the approximatly 12 x 12 screen. There was room in the display list for 8000 3-dimensional points or lines. This system was capable of hardware rotations to speed the cycle time for dynamic display.

Interface between the Megatek and computer was done through a user common where all display information could be

Fig. 3.1: E-2 Manipulator

stored until a command was called to send the information to the Megatek all at once.

3.4 Analog to Digital Converter

An Analogic 5400 Series was used to convert analog signals to digital for computer input. It also had inputs that could convert simple on-off signals to digital numbers. The six analog channels giving the joint angles of the manipulator could be read in about 300 microseconds on the parallel interface.

4.5 Trackball

The Measurement Systems Inc. Trackball was connected to the computer through a serial interface. It had a resolution of 512 for 360 degrees of ball travel and would output the number of units travelled between each send to the computer. The send rate was set by a baud rate of 9600. The Trackball was sensitive to motion around both x and y axes but not around the z axis.

4.7 Raster Display

A Lexidata 3400 Vidio Processor was used for raster display. It had a resolution of 640 x 512 pixels with each pixel having 256 possible shades. The shades were stored in a lookup table where they could rapidly be changed.

CHAPTER 4. TOUCH SENSORS

A touch sensor is required that will respond when it comes in contact with a solid surface and has to be configured in such a way that the exact location of the contact point can be determined. Many different types of sensor switching devices can be imagined. Switches based on pneumatics, stess, strain, or electical inductance might have good applications in different environments but for experimental purposes simple electical switches were used. Whatever the sensing device, it must be converted into an electical signal for the computer. The configuration of the touch sensor was found to be much more important than the actual sensing mechanism.

4.1 Best Configuration

4.1.1 To Sense Touch Direction or Surface Direction

When reading the three dimensional coordinates of a point on a surface it is also useful to find a vector pointing the direction of the surface normal at that point. This would give valuable information about how the surface is structured. The problem is that two degrees of freedom will have to be added to the touch sensor to enable it to read a surface normal, see Fig. 4.1. Adding more degrees of freedom significantly increases mechanical complexity,

the amount of data that must be transmitted to the computer, and computation time. There is another problem in that the surface normal would be be found for only one small spot. The surface normal in the immediate neighborhood of the point would only be implied. The average surface normal over a larger area could be found but would be at the expense of resolution of the point location. The surface normal could be found more accuratly if the points touched were densely packed, but then the points themselves describe the surface normal.

Although the ability to sense the direction of the surface normal would increase the surface description capabilities of a touch sensor, it was decided that it was not worth adding two more degrees of freedom. Since three adjacent surface points describe an average surface normal, it was felt there was no need to find it for every single point.

It was found to be useful, though, to record the touch sensor direction for each point. This was actually the center line of the touch sensor at the instant a point was touched. The touch direction was easily found because it had to be known to calculate the coordinates of the point anyway. The touch direction was useful because it defined a line that could not pass through the surface. This helped to define inside from outside. A series of points on a plane can describe a surface normal but cannot, by

themselves, describe which side of the plane is the outer side.

4.1.2 Rigid or Flexible Base

A touch sensor mounted rigidly to the manipulator would be more reliable and accurate than one mounted on a flexible base. The mathematics required to find its coordinates would be simpler and so would its mechanical complexity. It might seem that a rigid mounted sensor would be the best. But there are some advantages to a flexibly mounted sensor that may outweigh its disadvantages. One advantage of a flexibly mounted sensor is that the manipulator would not have to come to a complete stop when a point was touched. The sensor could just bend out of the way and not impede the continuous motion of the manipulator. This would allow faster motion of the manipulator and would reduce the risk of damage to the manipulator, sensor, or the object to be touched. Another advantage would be that many sensors could be used at once if they were all on flexible mounts. When one sensor hit a surface, it could respond and then bend out of the way to let the next sensor touch, see Fig. 4.2.

Flexible-base touch sensors could be constructed with or without degrees of freedom. The type without degrees of freedom would only work when straight, then simply shut off when bent over so as not to register any erroneous points. If the sensor had one or two degrees of freedom, it could

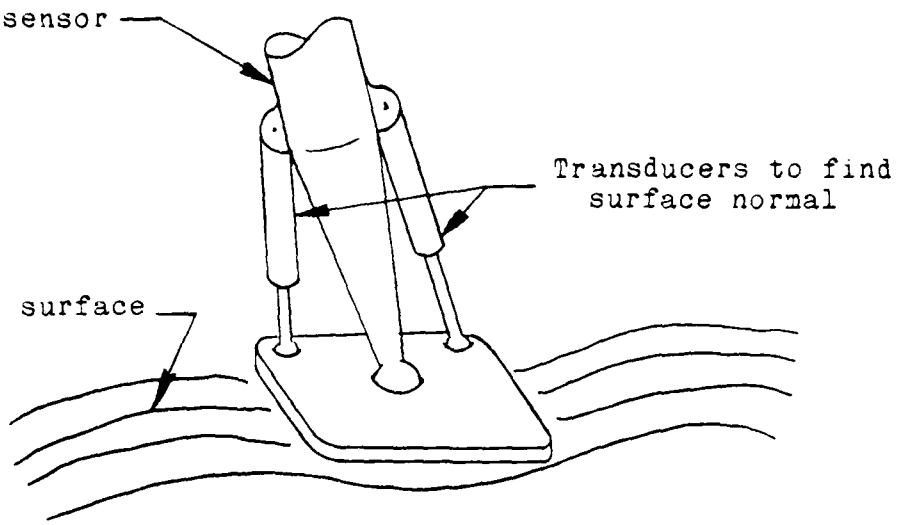


Fig. 4.1: Touch Sensor with Surface Normal Touch Sensing Capability

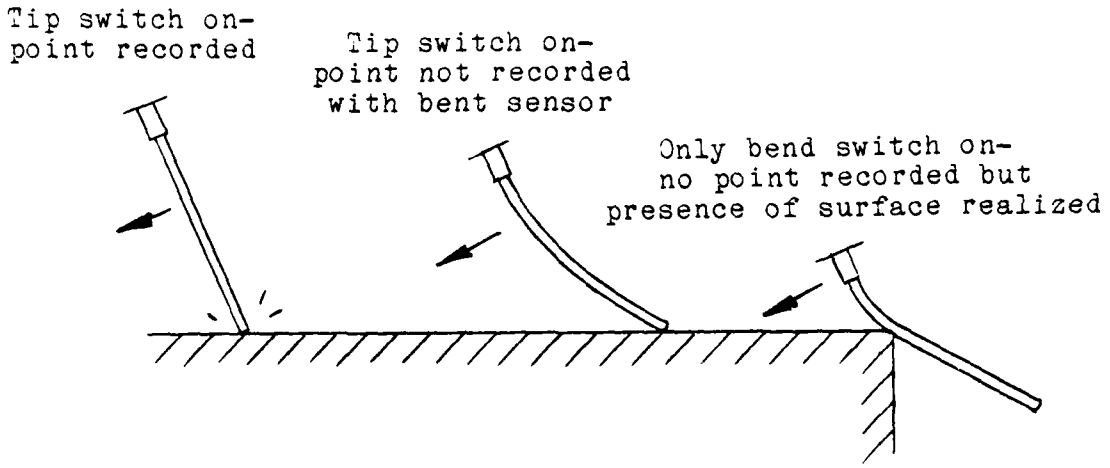


Fig. 4.2: Flexible Base Touch Sensor

still register points even when bent over, see Fig. 4.3. This way, a continuous stream of points could be read in one motion. The trade off would come when deciding whether it is more important to have fewer degrees of freedom or the capability to read many points with one sensor.

4.1.3 Where to Mount the Sensor

Since the sensor is to work with a manipulator, the most likely place to mount the sensor would be on the manipulator itself. If the sensor were mounted at the wrist of the manipulator, the sensor would have six degrees of freedom and be most maneuverable. If it were too awkward to use the wrist, the next best mount would be the forearm of the manipulator. This would reduce the number of calculations required to locate the sensor in space but would still leave three degrees of freedom.

The sensor could theoretically reach any point in front of the manipulator but the sensor would only be able to approach any one point from one direction. The sensor would not be able to reach around an object in the way, see Fig. 4.4. A solution might be to install many sensors on the arm protruding in all different directions so as to be able to reach all points with at least one sensor, see Fig. 4.5.

The very best mounting location would be to have the sensor mounted on its own arm. This could run completely independent of the manipulator and be controlled by a

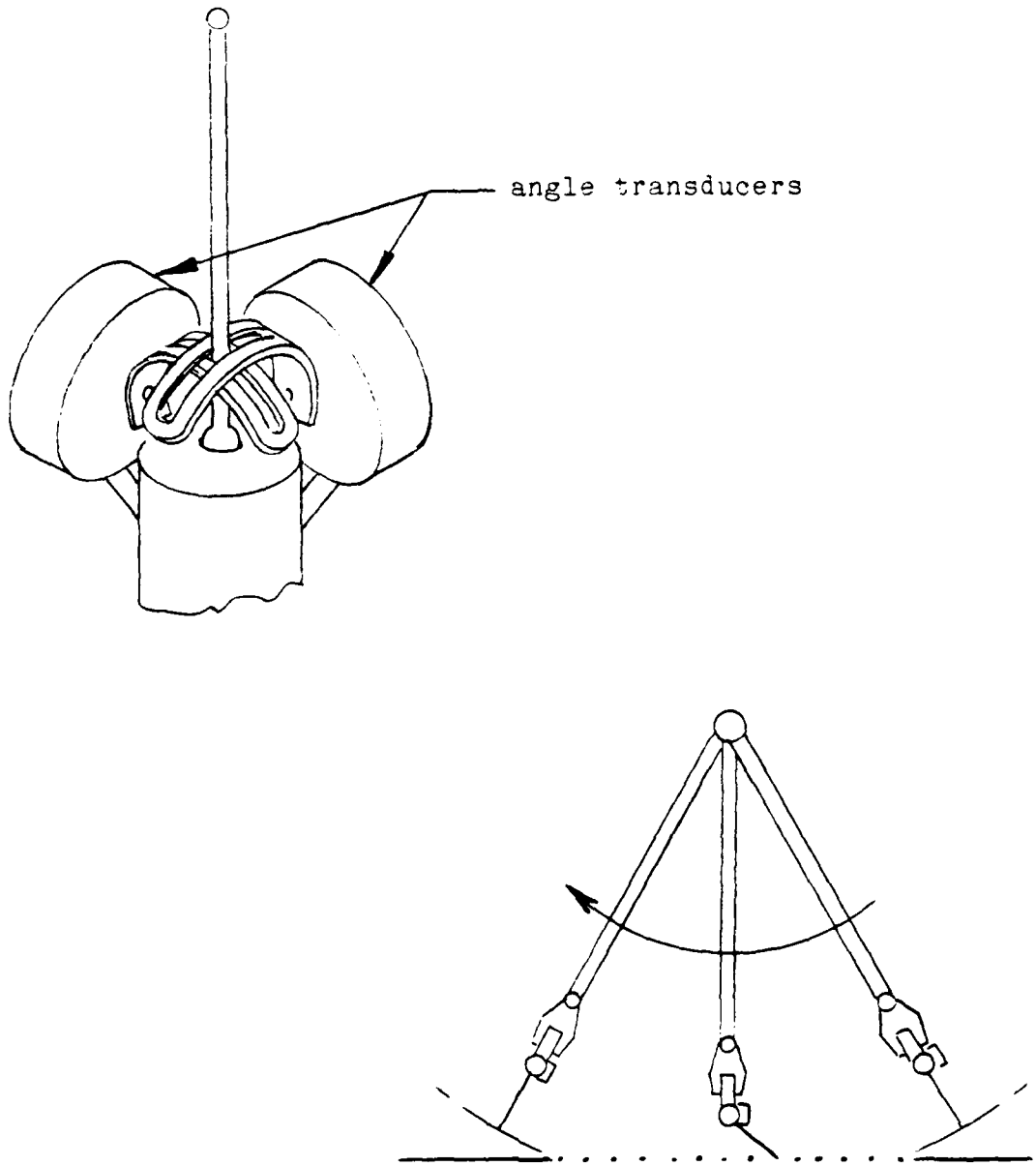


Fig. 4.3: Touch Sensor with Extra Two Degrees of Freedom

A long string of points could be recorded with one sweep of the manipulator.

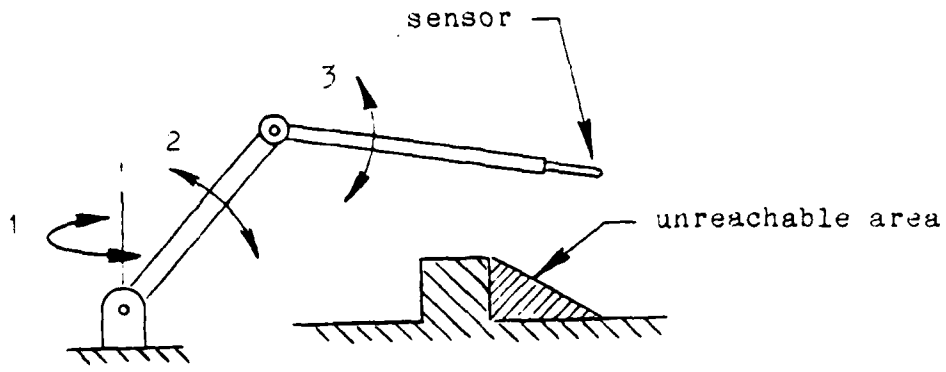


Fig. 4.4: 3 Degree of Freedom Manipulator with Interference Problem

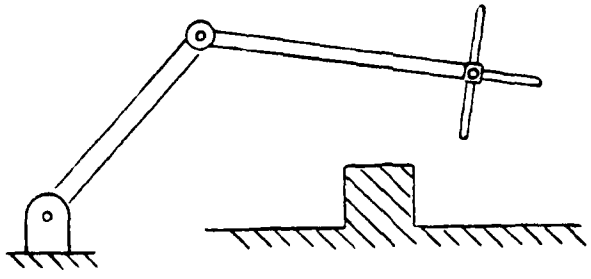


Fig. 4.5: Solution to Interference Problem

Several mounted touch sensors could reach more areas and would not increase the degrees of freedom of the manipulator.

different operator or perhaps be completely controlled by computer. A computer could be programmed to randomly sweep the sensor around and to concentrate on relatively untouched areas.

4.2 Touch Sensors Used in Experiments

The touch sensors that were built for experiments were designed solely to get surface points into the computer as efficiently as possible. The touch sensors were always mounted firmly in the jaws of the manipulator and only on-off electrical switches were used to send signals to the computer.

The first sensor built had 10 switches on it and each was connected seperately to digital inputs on the analog to digital converter, see Fig. 4.6. The switches were mounted on somewhat flexible stems and were arranged like a brush. It was found that a shorter stem provided the most accurate point coordinates and a slight convex curve to the profile of the endpoints of the stems allowed the sensor to be rocked across a surface to collect a maximum amount of points.

This brush sensor had some problems that made it difficult to use. The biggest problem was that the switches worked only when pressed from one direction. When a switch was hit from the side nothing would happen. This meant the sensors always had to be pointed in the direction the

manipulator was being moved to make sure the switches would be hit straight-on. Another problem was the sensors were too far from the base of the manipulator wrist. It turned out that the joint angles of the wrist could not be calculated accuratly and errors multiplied the farther the sensors were from the base of the wrist.

The second sensor built had only one switch on it, see Fig. 4.7. This was because in later experiments it was desirable to be able to select individual points on a surface. Also, the second touch sensor was located such that one degree of freedom of the wrist was not needed to calculate the sensor's coordinates.

Although the brush sensor had many more switches on it, the second sensor could collect points just about as fast. This was because the second sensor was made to be sensitive when approaching a surface from any direction, see Fig. 4.8. Besides being easier to maneuver than the brush sensor it could also be moved faster because the manipulator only had to move at the wrist to trigger the switch. The brush sensor required that the entire manipulator be moved to get the switches to approach the surface from the correct direction.

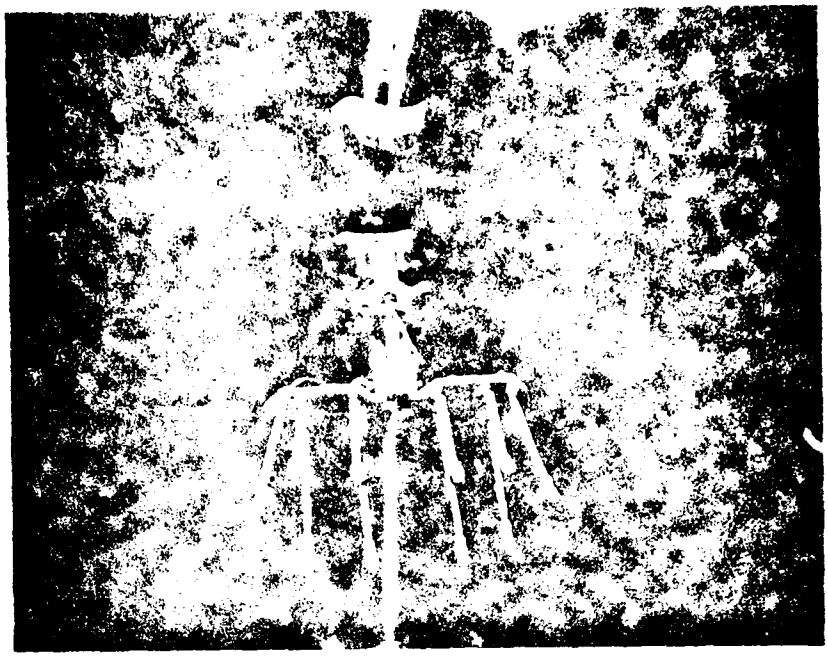


Fig. 4.6: [illegible]

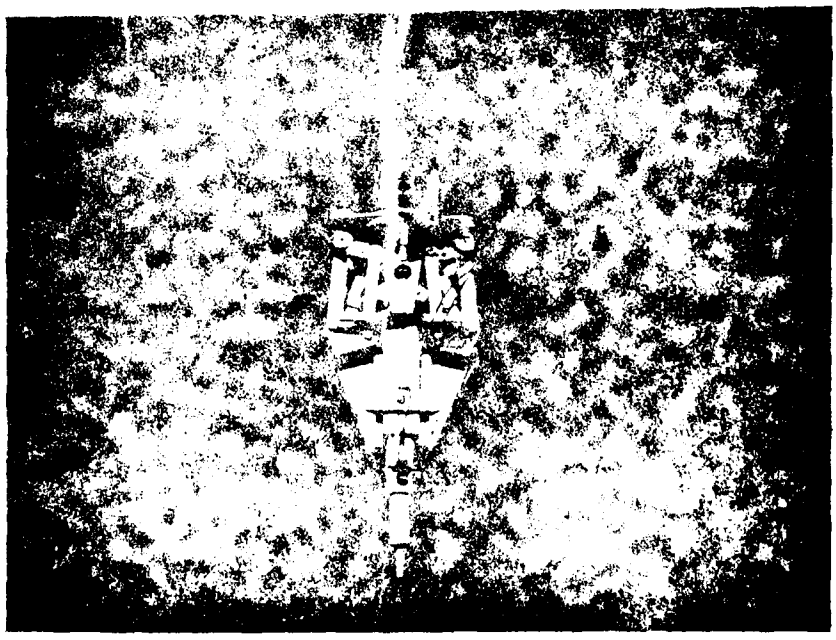
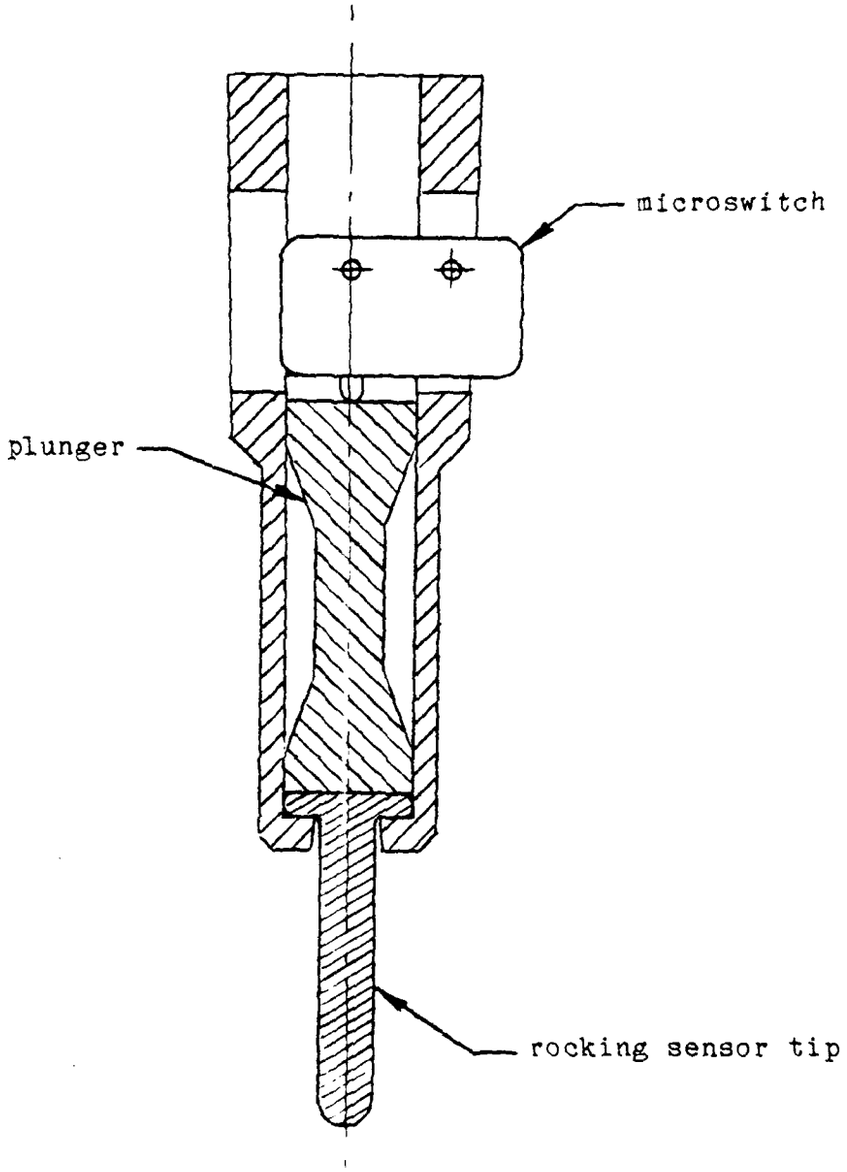


Fig. 4.7: [illegible]



SCALE 2/1

Fig. 4.8: Switch Mechanism that is Sensitive to Touch from All Angles

CHAPTER 5. CALCULATION OF POINT COORDINATES

5.1 Description

The picture of the manipulator was refreshed about every 20 milliseconds while the touch sensor program was running. To do this, the new angles of the manipulator had to be read every cycle. The coordinates of a touch point would be calculated during the cycle also whenever a touch sensor was activated. This was done by computing the sequential angular transformations from the base of the manipulator to the touch sensor tip. Intermediate transformations from each manipulator link were saved so the manipulator itself could be drawn on the graphic display. The coordinates of touch points were calculated and stored using the manipulator base as a relative origin and the x, y, and z axes were as shown in Fig. 5.1. Only integer values could be sent to the display processor so length units were chosen such that there were 40 units per inch. These units were chosen to minimize round off error and at the same time not overrun the display processor maximum length values, (plus or minus 2048). The basis for the dynamic display of this manipulator was developed by C. Winey and is explained in some detail in Ref.[1].

5.2 Problems with the Manipulator

The manipulator that was used to maneuver the touch

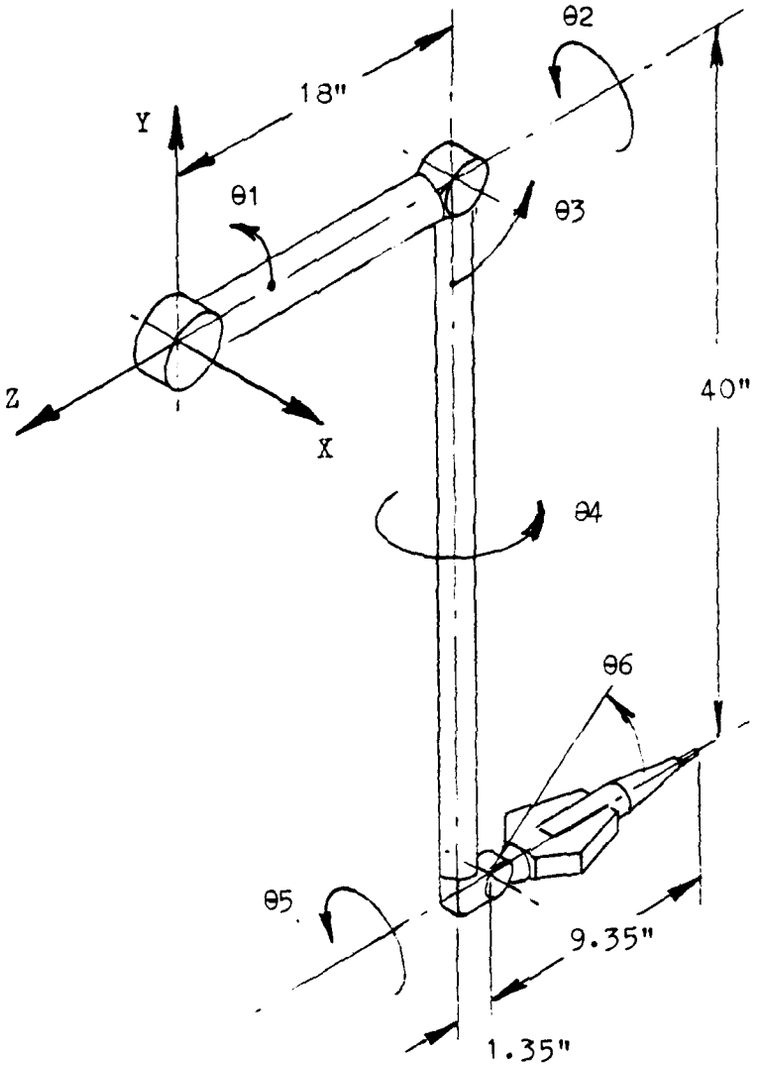


Fig. 5.1: Manipulator Coordinate System

sensor was built to be controlled by a human who would have direct visual feedback as to where he was moving it. This type of control system did not require accurate positioning because it was assumed the operator would compensate for errors. Consequently the manipulator was not very good for finding absolute point locations. This posed some unique problems to getting accurate point angles. The problem could be rectified by using a more rigid manipulator with less elasticity and "free play".

5.2.1 Cables and Gears

The joints of the manipulator were connected to the servos and position transducers by a series of cables and gears. This allowed for much backlash and flexibility which translated into errors for recorded joint angles. Any error in joint angles in turn translated into larger errors in calculated point coordinates. One way these errors were minimized was to make the touch sensor sensitive to very light pressure to reduce the strain on the cables. Another solution was to minimize the effect joint angle errors had on point coordinates. The wrist joints were most prone to errors because they were connected with the longest cables. Their effect was minimized by keeping the touch sensor as close to the base of the wrist as possible.

5.2.2 Pushrod

The elbow joint of the manipulator was connected to its servo and transducer by the pushrod arraingement shown in Fig. 5.2. At first it was thought that the gear angle Ag would respond very much the same as the elbow angle Ae and that they could be considered as equivalent. For relative motions this worked well enough but for calculating absolute point locations, the long forearm length multiplied a small angle error into a large position error. Fig. 5.3a shows the calculated locations of points on a flat square grid when it was assumed that Ag and A3 were the same. Clearly this assumption is invalid for absolute positioning.

An equation had to be developed to calculate the elbow joint angle A3 from the two angles it was dependent on, Ag and the X motion angle A2. A closed solution for A3 would be very long because the linkage was 3-dimensional and relatively complex. This was to be avoided if the calculations were to be done in real-time. Since the angle A3 was to be calculated for small incremental changes on each cycle it was decided to use the previous value of A3 on some preliminary calculations when figuring the new A3. Guessing the new value of A3 could eliminate some long calculations that really did not have much effect on the final answer. The method used was to calculate the x, y, and z locations at each end of the pushrod using Eq. 5.1.

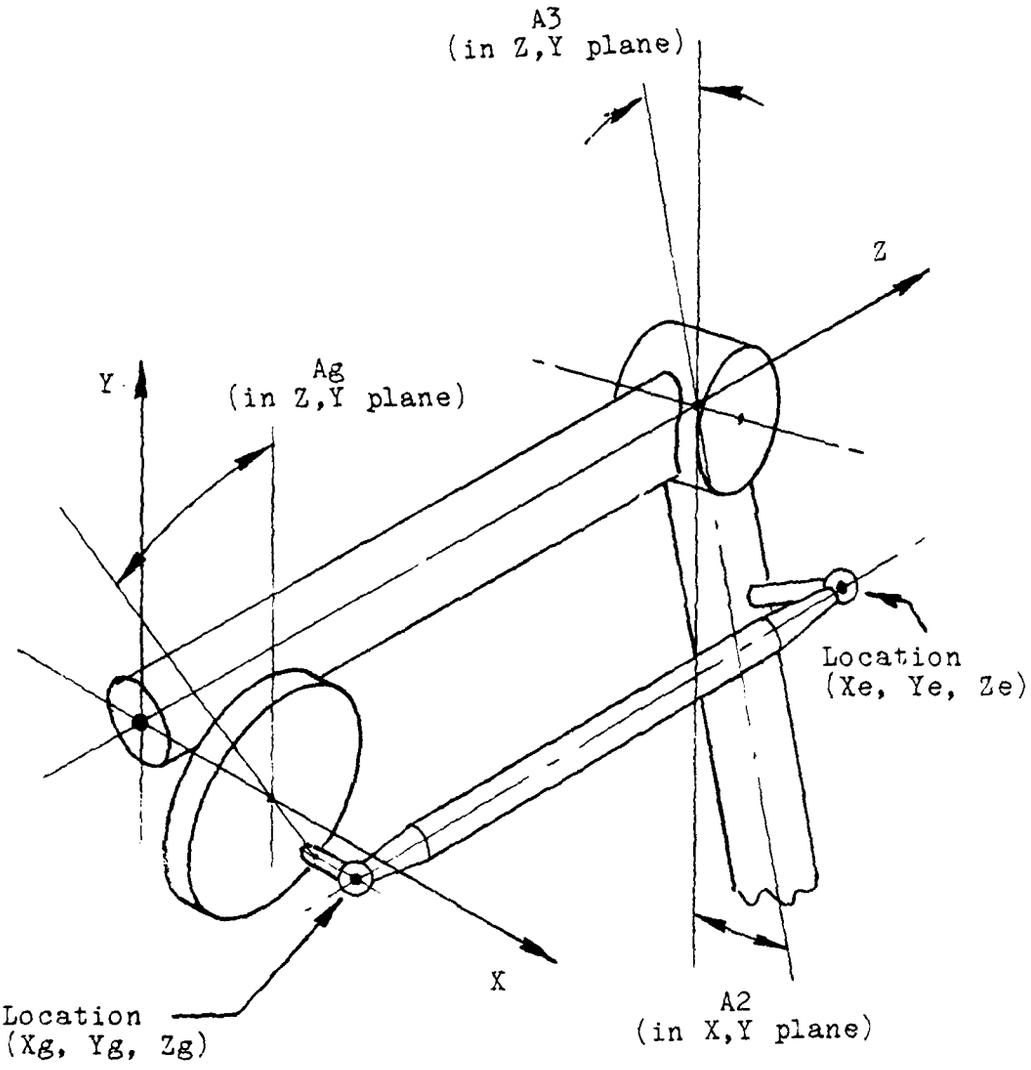


Fig. 5.2 Nonlinear Pushrod

(5.1)

a) $Xg = 3.10$

b) $Yg = -4.5 \sin(Ag)$

c) $Zg = 4.5 \cos(Ag)$

d) $X3 = 2.25 \cos(A2) - 4.5 \sin(A2) \cos(A3)$

e) $Y3 = 18. + 4.5 \sin(A3)$

f) $Z3 = 2.25 \sin(A2) + 4.5 \cos(A2) \cos(A3)$

The pushrod length was known to be 18.02 inches and could also be defined in Eq. 5.2.

(5.2) $$18.02 = \sqrt{(X3 - Xg)^2 + (Y3 - Yg)^2 + (Z3 - Zg)^2}$$

Between Equations 5.1 and 5.2 there are 7 equations and 9 variables. The two variables A2 and Ag are known so all the others should be defined if the equations are all linearly independent. The problem is that A3 appears 3 times, once in a sine function in Eq. 5.1e and twice in a cosine funtion in Eqs. 5.1d and 5.1f. This makes the problem of calculating A3 very nonlinear and makes it useful to do some guessing. If it is assumed that A3 is usually near zero, then small errors in A3 will have little effect on cos(A3). That means it should not make much difference if the value of A3 from the previous cycle is used to

calculate cos(A3) in Eqs. 5.1d and 5.1f. If this is done then it is a straight foward problem to calculate the new value of A3 from Eq. 5.1e. Equation 5.2 can be converted to:

$$(5.3) \qquad Y3 = Yg + \sqrt{18.02^2 - (X3 - Xg)^2 - (Z3 - Zg)^2}$$

And from Equation 5.1e ;

$$(5.4) \qquad A3 = \arcsin((Y3 - 18.)/4.5)$$

This method of calculating A3 worked very well even when the angle of A3 went up to 60 degrees. A value of A3 was converged upon fast enough that only one iteration per cycle was required. Figure 5.3b shows how points were located on a square grid with the angle A3 computed with the above routine.

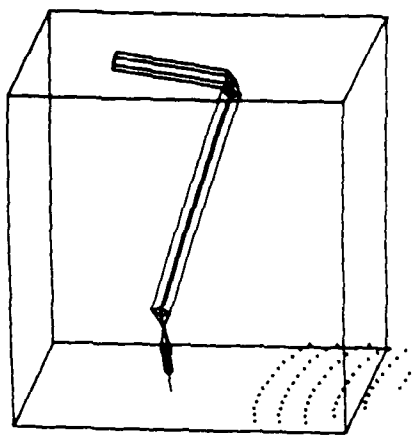


Fig. 5.3a: Grid Errors Due to Pushrod Nonlinearity

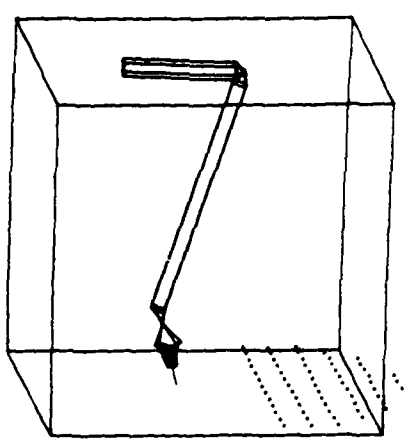


Fig. 5.3b: Grid Errors Reduced with Compensation

CHAPTER 6. POLYHEDRA CONSTRUCTION

6.1 Introduction

The previous chapter described a method of finding 3-dimensional point locations on a surface. It became apparent later that it would be very useful to have a way of describing the surface the points where found on. To have a geometric description of the surface would make it feasible to delete hidden lines and surfaces because a definite edge would be defined. It would also provide a basis for deciding inside from outside and make it possible to calculate volume and surface area.

First, simply connecting each point to its three nearest neighbors on the graphic display was tried. This had disappointing results because the lines tended to cluster in small bunches and didn't interconnect very much. The approach was discarded because it didn't give any semblance of a closed object and was no better than bare dots for making a recognizable picture.

It is a trivial problem for human to connect a given set of points with lines to make a closed shape so it would seem that a solution solvable by a computer would be possible. The problem is a human can make a judgement based on the whole set of points at once while a computer can only operate on a very small portion at a time. This means an iterative process must be found to construct the surface

with the aid of a computer.

It was decided to treat the surface as a geometric polyhedron (this is what the surface would come out as anyway if the surface is constucted properly). Also, a constraint was imposed that the polyhedron surface be made up entirely of triangular facets. This was done because it provides the computer the simplest possible surface segments to process. Also, triangular facets give the greatest resolution for a given number of points. A four sided facet connecting four dots would be the same as two triangular facets without the cross line.

6.2 2-Dimensional Solution

The 2-dimensional solution to the problem will be shown first because it has many analogies to the 3-dimensional solution but is much easier to explain. In this case there are points scattered randomly on the edges of a flat area in two-space. The problem consists of finding the best way of connecting the points to enclose the area and describe its edge, see Fig. 6.1.

The problem is fairly trivial if the area in question is completely convex. The correct way to connect any combination of edge points will always come out a convex polygon and any wrong solution will have some lines that cross over one another. This suggests an algorithm where a computer could try every possible line connection

combination until it came across a solution where there were no crossing lines. The trouble is that the number of required trials would go up exponentially with the number of points to connect.

The solution to this problem that is most similar to the one used to solve the 3-D problem is an iterative approach. First, any 3 points are connected with lines to form a triangle. Now if the area is still convex then all the other points lie outside this triangle.

It is important at this stage to define inside from outside for each line because the computer will only consider one line at a time. It can be seen from Fig. 6.2 that the three lines of the triangle can be defined as 1-2, 2-3, and 3-1 assuming that the x-y locations of points 1, 2, and 3 are known. The line 1-2 can be thought of as a vector with base 1 and end 2. Now the outer side this vector can be defined arbitrarily as its right side.

After the initial triangle is made and inside and outside defined, it is a straightfoward problem to add each point onto the existing polygon. An example is shown in Fig. 6.2. Point 4 is to be added to polygon 1-2, 2-3, 3-1. It is apparent that line 1-2 is the only one that faces out toward point 4, (there will always be just one such line if the area is convex). Now the line 1-2 can be deleted and the lines 1-4 and 4-2 added to make a new polygon 1-4, 4-2, 2-3, 3-1. The only decisive task for the computer is to

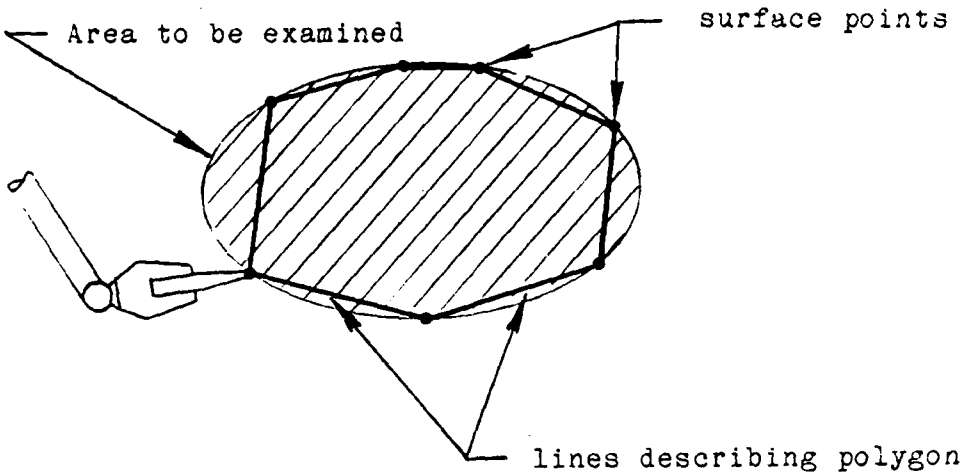
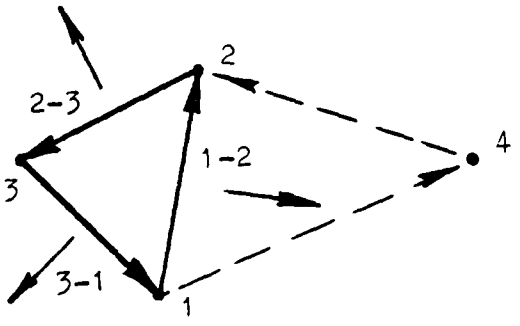


Fig. 6.1: Connecting 2-D Surface Points into Polygon



sequence specifies point connection
and outer side of each line

Fig. 6.2: Definition of Lines and Polygons

find the line which is best to attach the point.

The problem becomes more complex if areas with concave edges are allowed. Many different polygons can be made from a given set of points if there are concave edges, see Fig. 6.3. What can be done to limit the number of possible polygons to one?

If it can be assumed that touch sensors were used to find the points, then data about the direction from which the point was approached will be available. A "touch vector" can be associated with each point to indicate its outer side, see Fig. 6.4. Note that the touch vector does not necessarily have to be at right angles to the edge touched. It is only the centerline of the touch sensor at the instant the point is touched. Now a single polygon solution is again possible if the constraint is imposed that the touch vectors cannot pass through the polygon, see Fig. 6.5. Also, for computer control, there will only be one line on the polygon available to attach a new point to, (if any). If the new point is found to be inside the existing polygon then the correct line to attach it to is the one the touch vector passes through.

Some problems can occur with convex polygons. It is possible to come across a point that has no line on the polygon that it can attach to without violating a rule, see Fig. 6.6a. In these situations, the point must be thrown out or set aside until the polygon is developed enough to

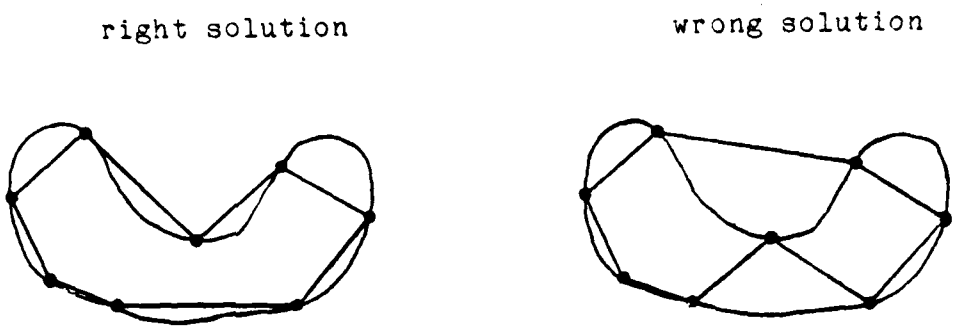


Fig. 6.3: Concave Polygons

In general, there are many ways to connect points found on a concave area and still get a closed polygon.

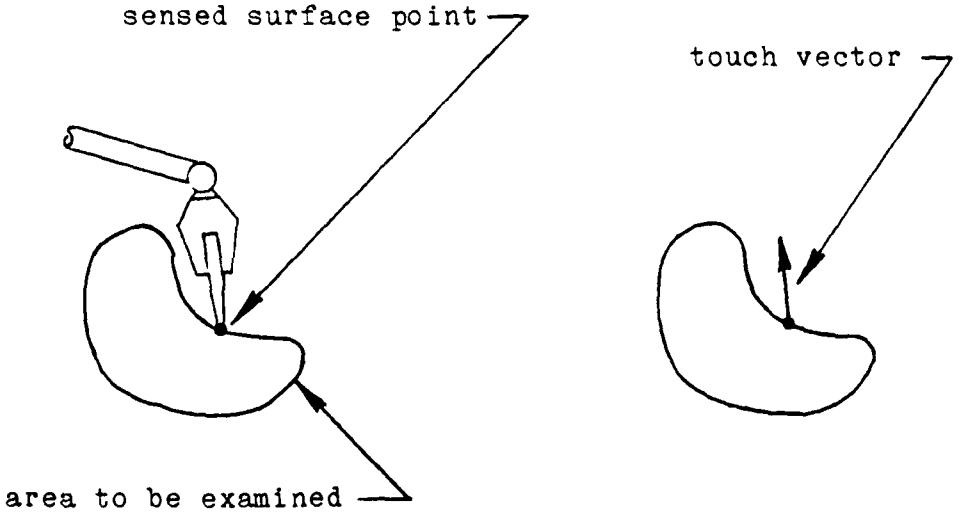
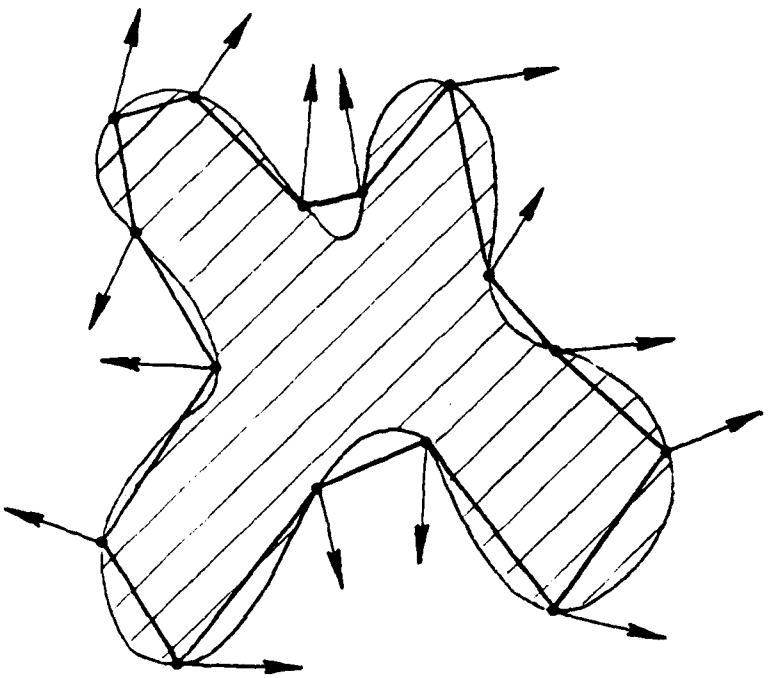


Fig. 6.4: Definition of Touch Vectors



touch vectors must always point
away from the polygon

Fig. 6.5: Constructing Concave Polygons with Touch Vectors

There will only be one polygon solution if touch vectors are considered.

accept the point. Another problem with convex areas is that a folded polygon can be constructed by the computer, see Fig. 6.6b. The solution to this problem is to ignore any point that has a touch vector that goes through any line on the polyhedron from its outer side.

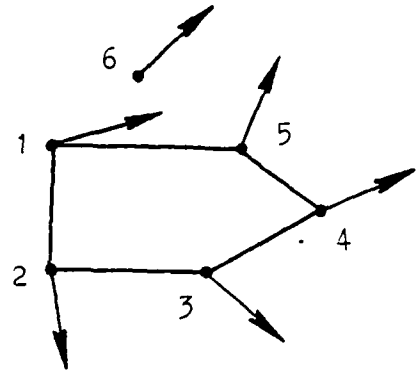
It is also possible to attach a new point to a completely erroneous line if a finite length touch sensor is used on an extremely convoluted polygon, see Fig. 6.7. This problem could be solved by putting a bend in the touch vector to more accurately simulate the touch sensor and its arm. An easier solution is to ignore points found to be over a certain depth inside the polygon.

6.3 3-Dimensional Solution

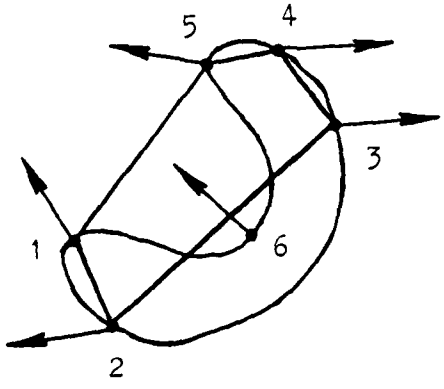
The problem here is to find a way to connect 3-D surface points with lines to make a polyhedron that closely resembles the surface the on which points were found. It turned out that the best way to solve the problem was not by analyzing the connecting lines but by analyzing the facets of the polyhedron. If the facets on a set of points is known then the edges are also known. Triangular facets were used as stated earlier.

6.3.1 Polyhedron Description

A method is required to store the facets in computer memory. It was decided to describe the facets as a sequence



a. Point 6 cannot be attached to the existing polygon without causing a touch vector to pierce through. It is not likely that point 6 is even from the same area as points 1 - 5.



b. Point 6 cannot be attached to the polygon without turning it inside-out. Point 6 will have to be ignored or saved until the polygon is further developed.

Fig. 6.6: Examples of Points That Cannot be Attached

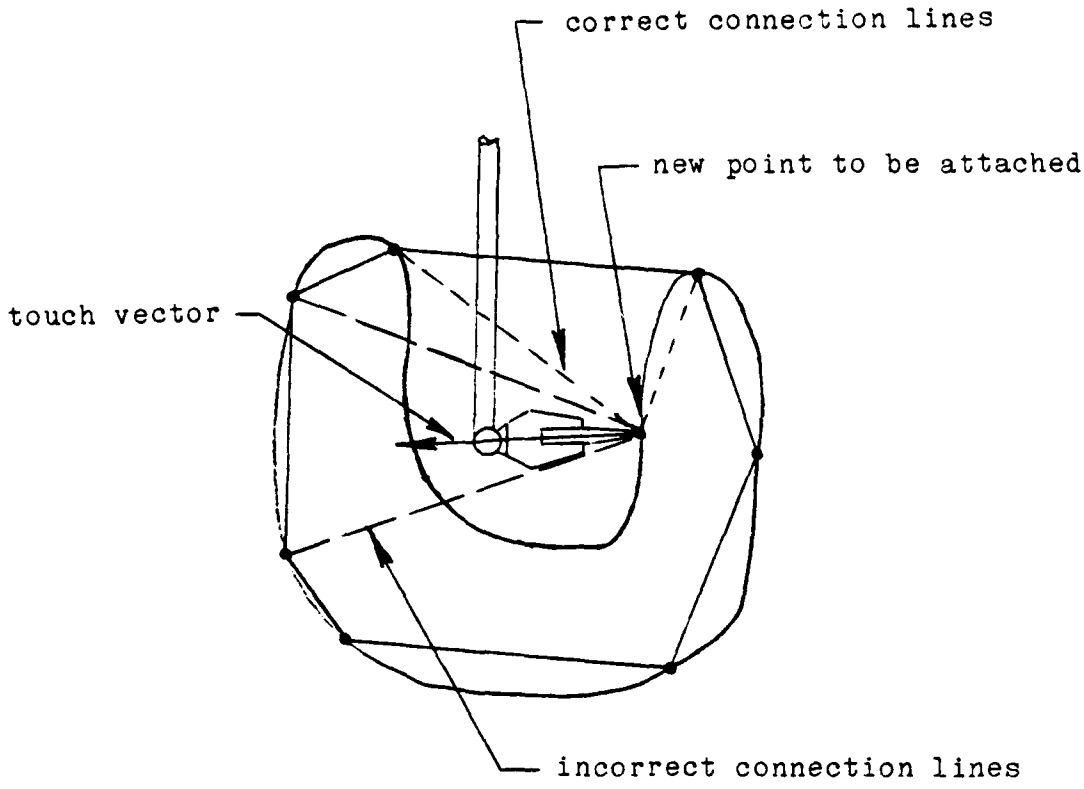


Fig. 6.7: Example of an Incorrectly Attached Point.

To keep the touch vector on the outside of the polyhedron, the touch point will have to attach to the wrong line. This problem stems from the fact that touch vectors are considered to be infinitly long while the actual touch sensor is very short. The simplest solution to this problem is to ignore or save points that are found to be deeper in into the polyhedron than the length of the touch sensor.

of points, because the points and their coordinates would be already known. The facet 1-2-3 would be a facet with edges connecting the points 1 to 2, 2 to 3, and 3 to 1. Also the inside and outside of the facet could be defined with this number sequence using the right-hand-rule, see Fig. 6.8. It can be seen that the facets 1-2-3, 3-1-2, and 2-3-1 all describe the same facet because the sequence always goes in the same direction around the triangle. The facets 3-2-1, 2-1-3, and 1-3-2 describe the same facet as above but with the opposite outside surface.

The computer description of a tetrahedron is shown in Fig. 6.9. Note that each line on a polyhedron is given twice in the facet data, once on two different facets and always in opposite sequence. It might seem easier to describe the polyhedron by storing the lines as two-number sequences rather than the apparently redundant method of storing facets as three-number sequences. But it turns out to be very important to know the complete facets and this data would not be readily available with line information.

Like the 2-D solution, restraints were imposed that restricted the configuration of the polyhedron. No surfaces were allowed to stick through one another and no touch vector could be allowed to exist on the inside of the polyhedron. Also, like the 2-D solution, an iterative approach was used where each point was added onto an existing polyhedron one at a time.

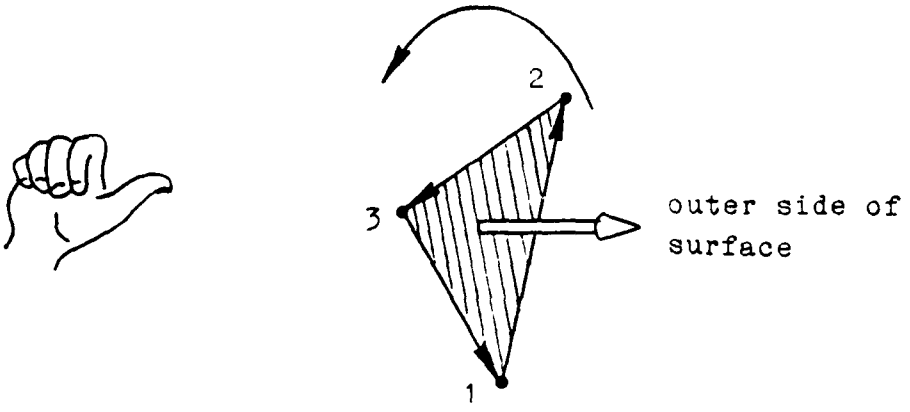


Fig. 6.8: 3-D Definition of Facets

Number sequence defines point connection and outer side of facet using the right-hand-rule.

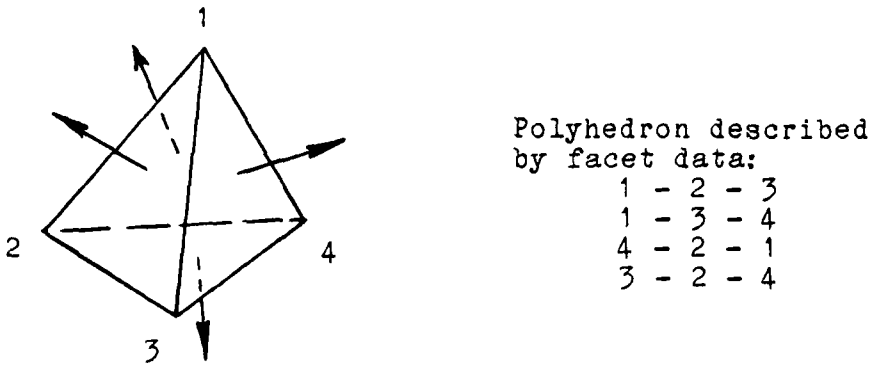


Fig. 6.9: Example of Complete 3-D Polyhedron

How can a new point be added onto a polyhedron? First, it is helpfull to exploit some of the useful properties of polyhedrons as described by Euler's formula for polyhedrons, where F is the number of faces on a polyhedron, E is the number of edges or connecting lines, and V is the number of vertices or points.

(6.1) $$F = E - V + 2$$

This equation holds for any ordinary 3-D polyhedron that does not have any holes passing through it.

Only polyhedrons with triangular facets will be considered so another defining equation is given. On a polyhedron with triangular facets it can be seen that each facet has exactly 3 edges and that each edge seperates exactly two facets. Thus:

(6.2) $3F = 2E$ (for triangle faceted polyhedrons)

Combining Eqs. 6.1 and 6.2 gives two relations.

(6.3) $$F = 2V - 4$$

(6.4) $$E = 3V - 6$$

Equations 6.3 and 6.4 show that for each new point added to a triangular polyhedron there will have to be 2 more facets and 3 more lines.

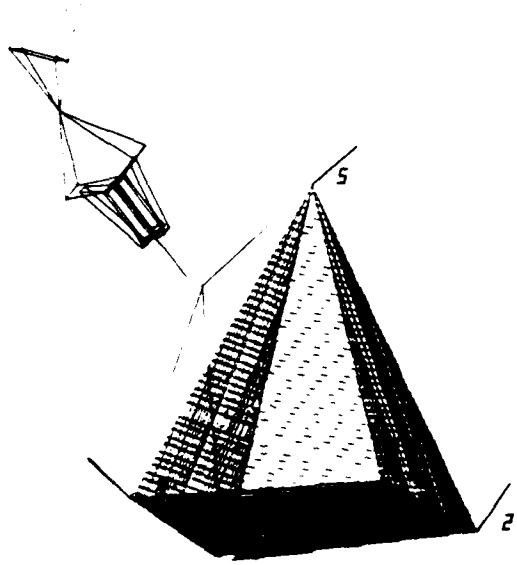
For the 2-D solution a point was added onto the existing polygon by deleting one chosen line and adding 2 more. In effect, the point was attached to the place were one line used to be. In the 3-D solution a facet must be chosen on the existing polyhedron on which attach the new

point. That facet is then deleted and the resulting hole is closed by adding 3 new adjacent facets that reached out to the new point, see Fig. 6.10. This procedure satisfies Equation 6.3, in the total number of facets added to the polyhedron for each new point. It is also apparent from Fig. 6.10 that Equation 6.4 is satisfied because exactly 3 new lines are added.

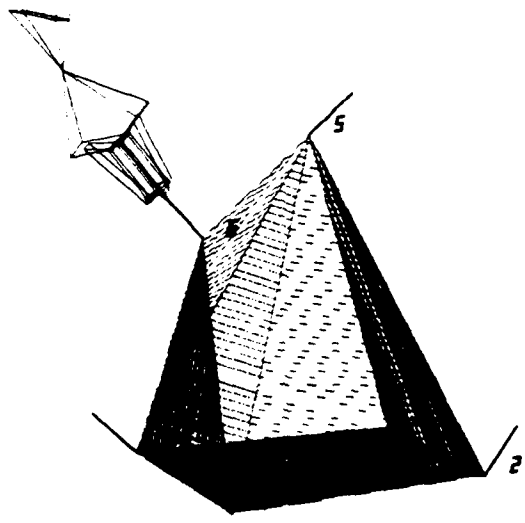
One of biggest problems was deciding which facet to attach the point to. Unlike the 2-D problem there was not always a single answer, even when touch vectors were considered. In general there could be several facets that a point could be attached to that would produce a closed polyhedron and would not cause any touch vectors to stick through any surface. More restraints had to be incorporated to make the computer converge on a single facet.

One restraint added to the program was that if a facet was pierced from the negative side of the touch vector of a new point, then that point must attach to that facet, assuming all the other restraints are satisfied. This restraint worked very well in situations where the new point was close to the polyhedron and the touch vector most likely passed through the best facet.

Sometimes, though, the new point was so far away that its touch vector did not pass through the polyhedron at all and if it did, the facet it pierced through was not likely to be the best. To cover these situations a secondary



a. Point 6 shown with chosen facet for attachment



b. Completed attachment

Fig. 6.10: Addition of new Points to the Polyhedron

restraint was added which required that the new point attach to the facet with the nearest centroid.

If the new point was very far away from the polyhedron, there would be very little chance the new point would attach to a good facet, see Fig. 6.11. The solution to this problem was to ignore points over a specified distance away. Taken together, these restraints caused the computer to converge on a single facet and usually it was the best one. Even when the chosen facet did not look like the best, the next step of processing usually converged on a better solution for the polyhedron.

Many times the new point was found to be on the inside of the polyhedron. In these cases there was at least one facet that could be found which the point's touch vector pierced from the inside. This was the only facet the interior point could attach to and keep its touch vector on the outside of the polyhedron, see Fig. 6.12.

6.3.2 Initializing the Polyhedron

The above procedure worked only at adding points to an existing polyhedron. A seperate algorithim was required to create a starting polyhedron from a set of initially unconnected points. The method used only required 3 points to make an imaginary two sided polyhedron. The computer was simply instructed that there were two facets, one on each side of the triangle defined by the 3 new points, see Fig.

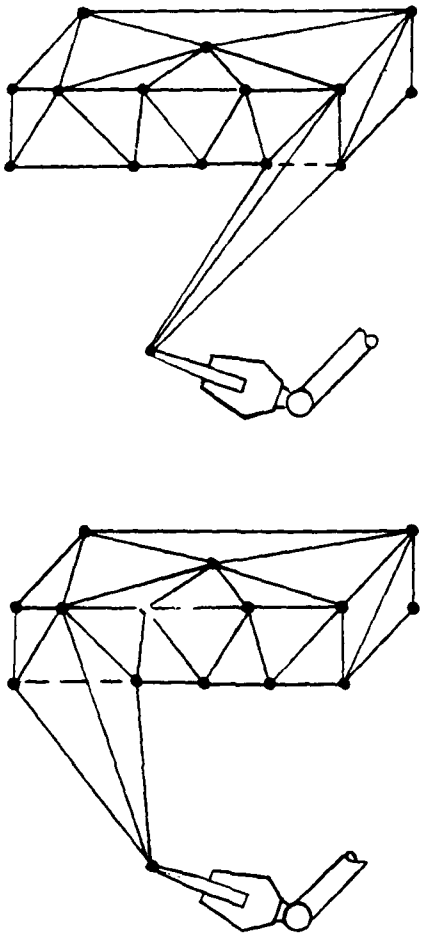


Fig.6.11: Possible Errors from Attachment of Distant Points.

In general, it is very difficult to make a rational decision on which facet to attach a distant point to. The choice, though, can have a drastic effect on the resulting shape of the polyhedron. The easiest solution to this problem is to ignore points that are over a certain distance from the polyhedron.

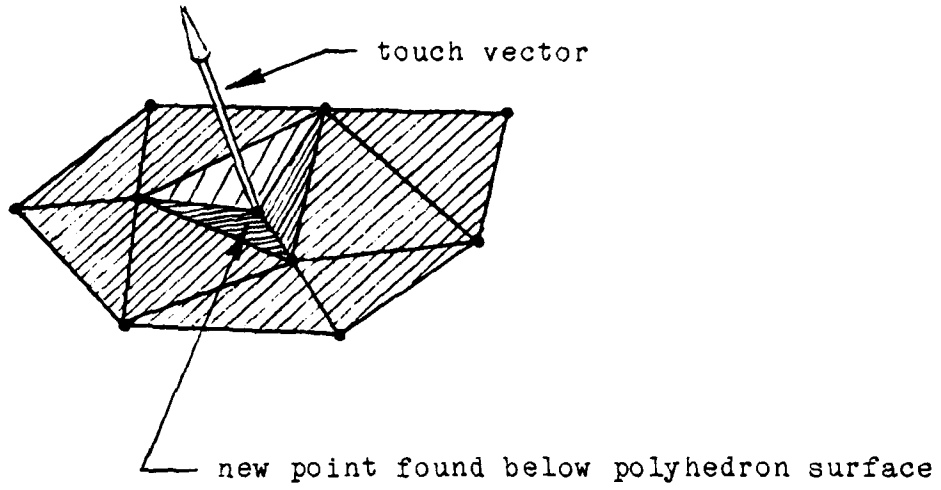
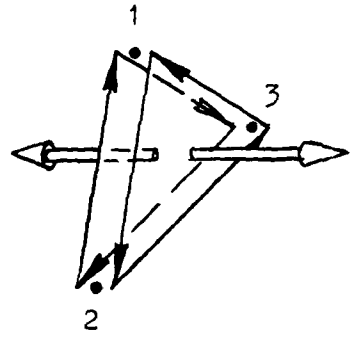


Fig. 6.12: Attachement of Interior Points

Interior points must always attach to the facet that the touch vector pierces through.



initialization facets
1 - 2 - 3
3 - 2 - 1

Fig. 6.13: Initialization of Polyhedron

First 3 points are connected with 2 facets to make psuedo-closed polyhedron.

6.13. The computer had no capacity to reject such an impossible polyhedron once it had been installed. Any 3 noncolinear points in space can be connected this way and will not technically violate any of the stated polyhedron rules. This entity also satisfied Equations 6.3 and 6.4 which specify the correct number of verticies, edges, and faces for a real polyhedron.

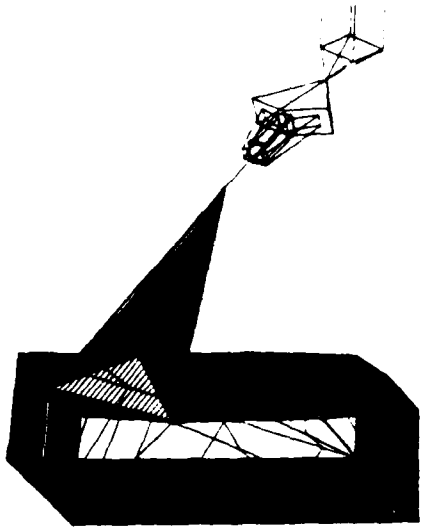
When the 4th point is added on, the computer will use the usual algorithm to erase one of the coplaner facets and add 3 more to make a tetrahedron. The reason that a tetrahedron was not used for initialization is that too much programing space would be required make sure the shape was not inside out and also that none of the touch vectors where piercing through.

6.3.3 Checking Facet Pairs

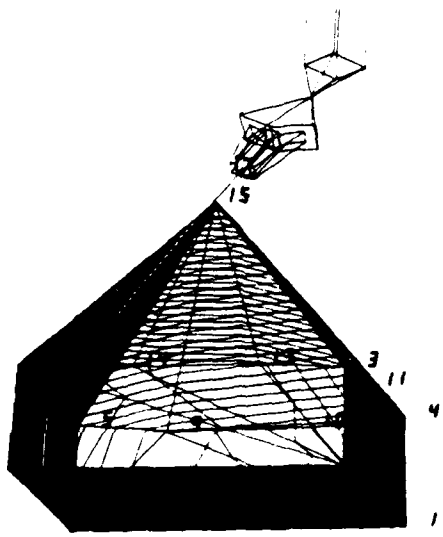
After a new point had been attached to the polyhedron, the facets were not usually in the best configuration. The new point could be sitting on the top of a long spike or otherwise looking as though it was stuck on as an afterthought, see Fig. 6.14.

Since there were usually many possible polyhedron configurations that a given set of points could be built into, some new critera had to be used to make sure that one polyhedron solution was decided upon.

The method chosen to modify the polyhedron was to check



a. New point attached to polyhedron without smoothing.



b. After smoothing.

Fig. 6.14: Need for Smoothing of Polyhedron

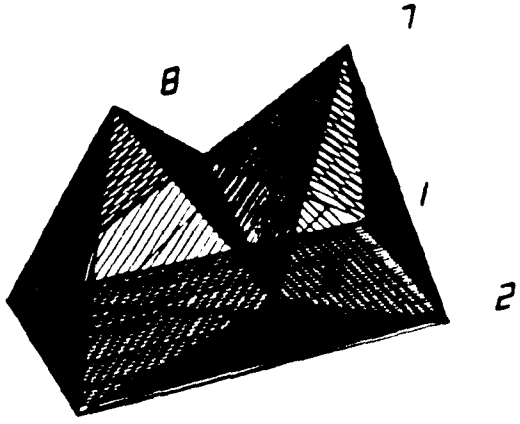
adjacent pairs of facets and, if required, replace them with compliment facets. Figure 6.15 shows how the four corner points connected by any two adjacent triangles could also be the corner points of two other completely different triangles. The facets 8-6-5 and 5-6-7 are the starting facets and 8-6-7 and 8-7-5 are the compliment facets. An entire polyhedron could be modified bit by bit by changing facet pairs and the polyhedron would never have to be considered as a whole.

The primary criterion used for deciding if a pair of facets should changed was based on the idea that a polyhedron with the smoothest surface will be the best. In other words a polyhedron would be seached for that had a minimum average angle between facets. This was done by comparing the pair of facets, considered for changing, to their four neighboring facets. The algorithm checked the angular difference between:

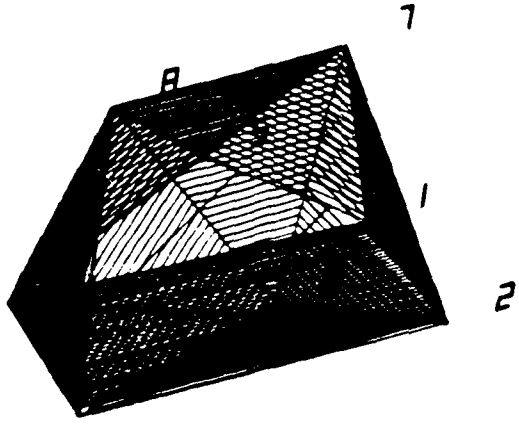
1) the original facets.
2) the compliment facets.
3) the neighboring facets and the pair to be checked.
4) the neighboring facets with the compliment facets.

This gave 5 angular differences to average for each of two polyhedron surfaces. If the complimentary facet arrangement was found to have less average angular difference, then the facets would be changed.

Several checks had to be performed when it was decided



Facet Pair 8-6-5, 5-6-7



Compliment Facet Pair 8-6-7, 8-7-5

Fig. 6.15 Example of a Facet Pair and Its Compliment

to change a pair of facets. New facets could not be allowed to stick through another surface of the polyhedron. Also, a check had to be made that none of the touch vectors of the points on the polyhedron pierced through the new facets. The change in facets would be stopped if any of the above happened.

It was possible to come across a pair of facets that had no reasonable compliment. These facet pairs were not considered changable and were found by checking to see if any of the compliment cross-lines were already occupied by other facets.

It would not be expected to find a touch vector that lay at an angle of greater than 90 degrees to the surface normal of an adjacent polyhedron facet. The computer, though, would construct a polyhedron this way if not instructed to consider touch vector angles. Therefore, another restraint was added that any facet pair had to be made convex if it had a corner point with a touch vector that pointed away from its surface normal at greater than 90 degrees.

The above requirements had to have certain priorities because they very often conflicted with one another. The order of priority was:

1) The polyhedron must remain a closed object and cannot be allowed to fold on itself or wrap inside out. Also all touch vectors must exist on the outside of the

polyhedron and cannot be allowed to stick through.

2) Any facet pair with a touch vector that pointed away at greater than 90 degrees from its surface normal had to be convex.

3) The facet pair that had the least average difference between themselves and their four neighbors had to be chosen.

When one pair of facets were converted, it affected all the neighboring facets as to whether they still followed the above requirements. This meant all these facets had to be rechecked.

The routine used to decide which facets to check was fairly simple. First all the facets were checked around the spot where a new touch point was added to the polyhedron. Then, if one of these facets was converted, all its neighboring facets were put in a list of facets to be checked. The routine stopped when the list was empty. Sometimes a pair of facets to be changed could get skipped over because the list was limited to 30 points. These facets would be found by using an operator controlled option that checked every facet pair on the polyhedron to catch any that were incorrect.

There was some concern that a polyhedron might be formed that would have a chain of mutually dependent facet pairs. In other words each facet change would cause the neighboring facets to change and an endless loop of changing

facets would be formed. The existence of such a polyhedron has not been proven but it was never observed to occur. The computer program would always converge on a polyhedron where all the facet pairs satisfied the requirements.

6.3.4 Quality of the Polyhedron Shapes

It might seem that there would always be one solution that the computer would converge upon. This was not always true. Sometimes the polyhedron would get into a bad shape the computer algorithm could not get it out of. This due to the fact that the computer algorithim based its decisions on only one pair of facets at a time. There was no way for the computer to get to better facet configuration if the first facet change meant putting the polyhedron in an impossible shape.

The method used to keep the polyhedron from locking into bad shapes was to make sure that new points were not added an unreasonable distance away from the existing polyhedron. If the maximum distance was held to within the general feature dimensions of the object being touched then the points would attach onto reasonable areas. It would be very difficult to attach a new point to a developed polyhedron in the right place if the polyhedron was roughly one foot across and the new point was more than two feet away, see Fig. 6.12.

CHAPTER 7. METHODS OF DISPLAY

7.1 Introduction

The 3-dimensional information needed to completely describe points and polyhedrons in space can be easily stored as data in a computer. But if these data are just displayed as lists of numbers, it will be absolutely meaningless to a human. A graphic display can show 3-dimensional data much better but suffers from the fact that it can only display a 2-dimensional picture. This chapter will consider different methods of bringing out 3-dimensionality for data to be shown on a graphic display.

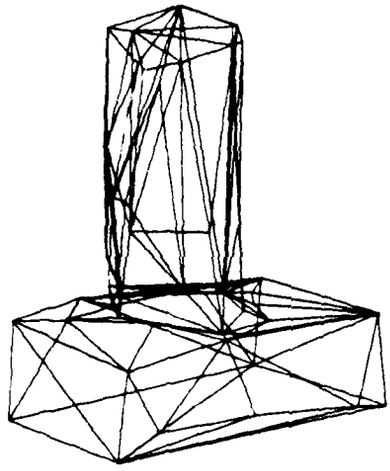
7.2 Problems with Polyhedra Displays

Most of the methods used to display 3-dimensionality described here were developed long before it was possible to create polyhedra from point data. It would have been very difficult to understand what was happening in the program without it. This was because it was impossible to tell what the computer was constructing in 3-D, without a good method of viewing it. A polyhedron drawn on a vector graphic display just looked like a mass of connected lines if hidden segments were not removed. There was no way to tell if one triangle was sticking though another triangle in 3-space when only one flat view was available, see Fig. 7.1.

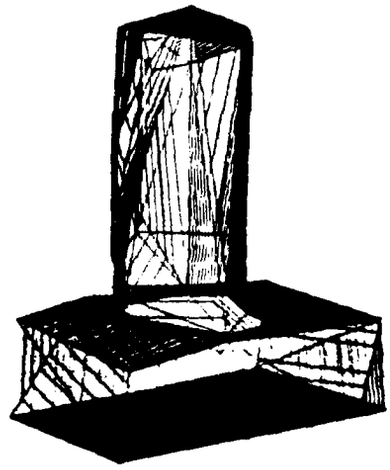
There are several ways to improve the depth of a flat

a) Photograph

b) Points Only



c) Polyhedron



d) Polyhedron with Contours

Fig. 7.1 Different Displays for One Set of Facets

picture. Showing perspective is one way but it is best suited to rectangular shapes. Triangles shown in perspective just look like slightly different triangles. Deleting hidden lines and providing shading are methods that bring out depth for a human but can be very slow to process in real time. A method using raster graphics to remove hidden surfaces will be shown later in this chapter but was only good at getting a static picture. C. Winey [1] did studies on showing two orthogonal pictures on the screen at once and displaying a shadow to help define 3-dimensionality. These methods worked well for displays where related features could be distinguished in each view and were used successfully for maneuvering the touch sensor on the screen. It was difficult, though, to distinguish related points on a complex polyhedron shown in dual views.

7.3.1 Rotating the Picture

It was found that rotating the polyhedron on the screen helped to bring out its 3-dimensionality. Features in the back of the picture moved one way and features in front of the picture moved the other way. Specific details could be seen also if the picture was rotated a full 360 degrees. For example, it could be seen whether or not a line was piercing a triangle if the picture was turned completely around. If a line was not piercing a facet, then there has to be at least one place in the rotations on the screen

where the line does not lay across the facet.

To give the appearance of a rotating picture, the object coordinates were calculated for a small incremental angle change and the picture was redrawn on the display. It was possible to redraw the picture rapidly enough to give the illusion of smooth rotation. The object could be viewed from any angle if it was first rotated about an axis. This could be done by multiplying the X, Y, and Z coordinates of the object by a rotation matrix [T] to get the new coordinates X', Y', and Z'.

(7.1) $$[\ X',\ Y',\ Z',\ 1\ ] = [\ X,\ Y,\ Z,\ 1\ ][\ T\ ]$$

where:

(7.2) $$[\ T\ ] = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(A) & -\sin(A) & 0 \\ 0 & \sin(A) & \cos(A) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

(for rotation around the x axis)

(7.3) $$[\ T\ ] = \begin{bmatrix} \cos(A) & 0 & \sin(A) & 0 \\ 0 & 1 & 0 & 0 \\ -\sin(A) & 0 & \cos(A) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

(for rotation around the y axis)

(7.4) $$[\ T\ ] = \begin{bmatrix} \cos(A) & -\sin(A) & 0 & 0 \\ \sin(A) & \cos(A & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

(for rotation around the z axis)

The orientations of the display coordinates and the object coordinates used for the above equations are shown in

Fig. 7.2a. A positive rotation is defined as counter-clockwise when looking down that rotation axis.

Since the display consisted of points in space either connected or disconnected, all that was required to be transformed was the coordinates of the points. The "connectivity" would not change no matter what the angle of view.

A combination of rotations could be made by multiplying the rotation matrices together. The equation;

(7.5) $$[\ T\ ] = [\ Tz\ ][\ Ty\ ][\ Tx\ ]$$

is equivalent to a rotation around the z axis, then around the y axis, and then around the x axis. It is important to keep the order of multiplication straight or different views will result.

It is convenient to describe all the terms of the transformation matix as shown in Equation 7.6.

(7.6)

$$[\ T\ ] = \begin{bmatrix} XX & YX & ZX & 0 \\ XY & YY & ZY & 0 \\ XZ & YZ & ZZ & 0 \\ XT & YT & ZT & 1 \end{bmatrix}$$

The terms XX thru ZZ handle rotations and their values are usually determined by equations 7.2, 7.3, and 7.4. TX, TY, and TZ are translational values that define the position of the object relative to its own coordinate system. These are important if it is desired to zoom in on a small section of the object. A zoom effect is possible by multipling all

terms of the transformation matrix by a size factor.

The Megatek Display Processor had the capability to do rotations in hardware. The 3 coordinates of all the points defining the features of the object were first stored in Megatek memory. Then it was given the required rotation terms and the Megatek would take care of calculating the transformations for each point. This saved having to do the calculations for each point in software and also reduced the amount of data that had to be sent to the Megatek. Very fast and smooth rotations were possible regardless of the complexity of the display. The transformation terms required by the Megatek were XX, XY, XZ, XT, YX, YY, YZ, and YT. The rest of the terms only affect the z plane of the display which cannot be seen on a 2-D screen.

The Megatek rotations always occured around the origin of the object as it was installed in display memory. This was inconvenient because very often a small portion of the display would be zoomed in on and would also need to be rotated. With the object rotating about its center the small portion would generally rotate right out of view. The cure for this was to cause the object to always rotate around in screen origin. The XT and YT terms sent to the Megatek affected the x-y positions of points in screen coordinates. These terms could be altered each time the picture was rotated to keep the object on screen center. To do this, the translations in object coordinates had to be

specified, (Xo, Yo, Zo). This was done by manuvering the desired rotational base to the center of the screen by viewing two orthogonal views. Now the picture would always rotate about that base if XT and YT were recalculated every iteration by the equations;

(7.7) $$XT = XoXX + YoXY + ZoXZ$$

(7.8) $$YT = XoYX + YoYY + ZoYZ$$

XX, XY, XZ, YX, YY, and YZ had to be calculated first for that rotation.

There is a problem with dynamic pictures that are rotated with the above transformations. There will be no indication which is front and which is back on an object when no hidden lines are removed and no perspective is shown. An object can be rotating on the screen and some people viewing it will say its rotating to the left while others say its rotating to the right. The mind tends to lock on one rotation and can be difficult to change. One way found to remedy the problem was to memorize the correct rotation for each input but it was too easy to forget. The most useful method was to have a known zero position the the picture could be put in, where front and back were known. Another solution might be to have a coordinate indicator on the screen consisting of writing. Front and back are easily distinguished with writing because it cannot be read when it is shown reversed.

7.3.2 Types of Rotation

Some methods of rotating the picture were better than others at showing depth qualities. If the picture was rotated about the z axis of the screen, there would be no changes made to the picture due to its depth. The same rotation could be done with a flat picture. Rotation on the x axis or y axis were better because points at different depth locations would move at different speeds. It was best to have the center of rotation somewhere near the middle of the object to get maximum contrast of motion due to depth.

Rotation around the x axis could be very disorienting because the picture goes upside down once every oscillation. This left rotation about the y axis as the best choice of the three.

Simply rotating about the y axis on the screen moved each point on the screen back and forth in the x plane. It was found to be helpful to tilt the entire coordinate system on the x axis first before rotating in the y axis. This caused descrete points making up the picture to move in ellipses on the screen. Ellipses gave a better indication as to exactly where each point was in the picture. A tilt downward around the x axis of about 15 degrees produced the most natural looking and informative picture.

7.3.3 Oscillating the Picture

Rotating the picture completely around gave the best

overall description of the object but when the display was being used to control the manipulator, it was hard to distinguish between front, back, and sideways, as they where always changing. A better way of moving the picture was found for situations where picture orientation had to be known. Instead of rotating completely around, the picture was just rotated back and forth with a sine wave controlling the y angle. This way the orientation was not disturbed much and the 3-dimensions were still apparent. An amplitude of 10 degrees with a period of 2 seconds produced a useful picture. The problem with this display was that the operator sometimes had to wait for the full cycle to finish before getting his bearings and making another move.

7.3.4 Rotation with a Joystick or Trackball

All the rotations done previously were controlled by the keyboard and did not require ,or allow, much direct attention. Sometimes it could be very useful to be able to position the picture in any view very rapidly. There was available a trackball and joystick that were built to provide this type of control. They could be wired to the computer to control the display angles.

7.3.5 Position Control

The 3-degree of freedom joystick that was used put out a voltage related to the position of the joystick. This

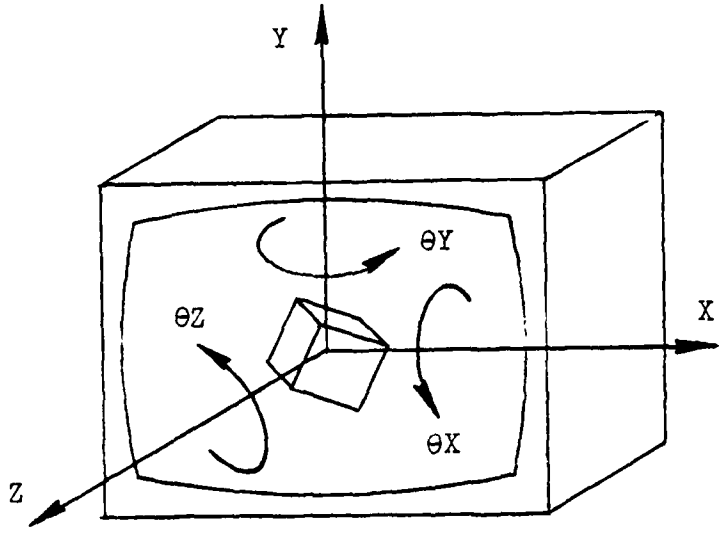
voltage was used to control the 3 angles fed into the display transformations matrix, as shown in Fig. 7.2a. The order of angle transformation used was, first rotation around the z axis, then the y axis, and then the x axis. It was important to transform the z axis first because that made the display move most similar to the joystick. A potentiometer was mounted on the joystick box to control the maximum allowable angles that the display could be put through. The display could be viewed from any angle but would bounce back to zero when the joystick was let go.

7.3.6 Velocity Control

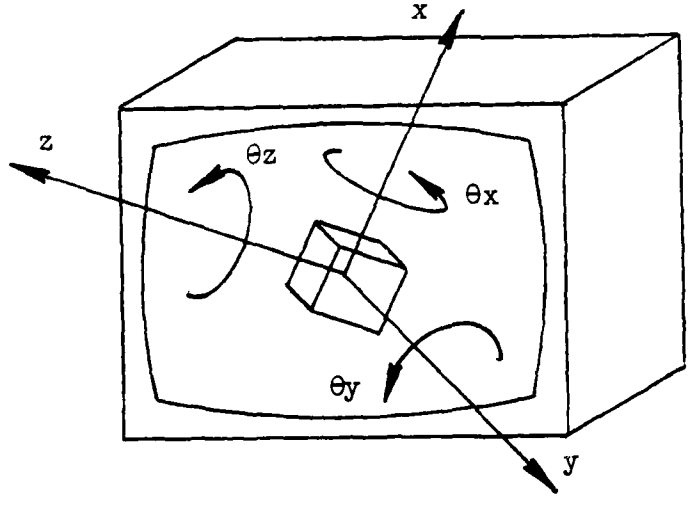
In velocity control it was most convenient to rotate the display in screen coordinates, as shown in Fig. 7.2b. This allowed the picture to rotate independently of of the orientation of the object coordinates. When angles are changed with respect to object coordinates it was not always apparent which way the picture would turn for a given input if the object was already rotated through some other angles.

The x-y inputs available from the trackball were sufficient to position the display because only two angular veloceties were required to maneuver the display when using screen rotations. With the joystick, all 3 inputs were used even though they were redundant. This allowed somewhat faster control of the picture position.

Rotation in screen coordinates was done with the same



a. Screen Coordinates and Rotations



b. Object Coordinates and Rotations

Fig. 7.2: Screen and Object Coordinates

transformation matrix as rotation in object coordinates. The difference is that the transformation was completely recalculated each cycle when rolling in object coordinates and was only modified for screen coordinates. The display transformation matrix was saved from the last iteration and multiplied by an incremental transformation matrix that was the same as the object transformation, but which reflected a very small angle change. It did not matter in which order the x, y, and z rotations were multiplied by the transformation because it made little difference for small angle changes. It would seem that the transformation matrix would degenerate from floating point round-off when it was continually remultiplied by another matrix but this was not observed to happen and the display did not seem to lose integrity even after many rotations.

For versatility, rotations in screen coordinates were found to be the best. Also, the capability to rotate directly on the screen z axis in addition to the x and y axes was useful and time-saving even though it was redundant.

7.4 Improving the Display for Polyhedra

7.4.1 Showing All Edges

The construction of a polyhedron out of a set of points offered several methods of improving display quality. The

obvious way to display a polyhedron constructed in the method shown in Chapter 6. was to just show all edge lines. The edge lines could be constructed from the facet data because each edge was defined twice, once in two different facets and always directed in opposite directions. The algorithm used to connect the points on the display simply went through the data and drew a line when two connected points on a facet were found in increasing order. A complete picture could be made of a polyhedron consisting of 40 facets in about 50 milliseconds.

This particular type of polyhedron display was used most frequently because it was so fast to construct. In fact this display was completely reconstructed every time a facet was changed. It did not produce an especially clear picture but rotating it did help. No attempt was made to remove hidden lines from this display because it would take too much computing time.

7.4.2 Drawing Contour Lines

It was a straightfoward problem to draw contour lines around the outside surface of a polyhedron, because the data for each of its facets were stored in memory. The only outside information required by the computer was the number of contour sections to draw. The gap between sections was automaticly figured from the overall size of the polyhedron.

The contours were all made on the z plane and each

contour was calculated and drawn in sequence. For each contour plane every facet in the polyhedron was checked to see if it passed through that plane. When one did pass through then the endpoint coordinates of the line segment defining the facet cut were calculated by interpolation. If the polyhedron was without holes or folded surfaces then the contour drawn at any section would be a closed polygon.

Drawing contours was found to be the best way display a polyhedron on a vector graphic display. The shape of the object was well defined by two aspects of the contours. One was that the directions that the contour lines went in gave an indication of the angle the facets had relative to the z axis. The other aspect was that the density of contour lines on one facet indicated the angle the facet had with respect to the z plane. The line density of the facets also produced a sort of shading effect that gave an immediate sense of 3-dimensionality. When the polyhedron with contours was rotated the picture became very well defined. Any errors in the polyhedron became painfully obvious because any facets sticking through other facets could be readily seen. Also if any facets folded over on top of each other the picture became very bright in that area.

7.4.3 Raster Graphic Display

Raster graphics was experimented with to see how well a 3-D polyhedron could be displayed. It was also used to show

how easily polyhedron data as described in Chaper 6. could be processed by a computer.

The difference between raster graphics and vector graphics is that the raster graphics beam sweeps out the entire screen and its picture is changed by variations in intensity like a television picture. The vector graphics beam traces out each of the lines and points individually. An advantage of raster graphics is that surfaces can be simulated better because shading is possible and it is also easier to delete hidden lines and surfaces.

The primary disadvantage of the raster display used in the experiments was that it was much slower at drawing pictures than the vector display. This made real-time rotations impossible so the raster graphics was used primarily to make static copies of polyhedra.

To draw a polyhedron on the raster display it first had to be constructed with the vector display. The polyhedron was then framed in the vector screen to the view desired to come out on the raster display. When this was done all the polyhedron data was stored in a data file. The 3-D point locations were stored in screen coordinates to preserve the view chosen for the display. This data was then read by a second program that put the polyhedron on the raster display. The triangles of the polyhedron were drawn one at a time on the display according to their x-y coordinates. The shade of each triangle was determined by comparing the

angle of the surface normal to a space vector simulating a light source direction. Triangles facing away from the screen were not drawn at all. It had to be known how the facets lay in 3-space and which side of each facet faced out to accomplish shading. This was another advantage of storing facets as described in Chapter 6.

If the polyhedron had any concave areas, it was likely that there were several facets partially hidden by other facets. By its nature, raster graphics will automaticly draw a new triangle right over an old one so all that is required is that hidden triangles be drawn before the non-hidden ones. The method used to draw the facets in the correct sequence was very simple. The point on each facet with the maximum z value (nearest point) was the only one considered to decide facet order. The facets were ordered such that the ones with a minimum value for this point were drawn first and ones with higher values were drawn last. There were some situations where this algorithm would give wrong answers but so long as the object to be displayed was not a radical shape and there were a reasonable number of facets defining each feature there would be no overlapping facets drawn in the wrong order. This type of shading display made the best picture when there were smooth transitions between facets.

It was found to be advantageous to be able to interactively change the location of the light source to a

position where the 3-dimensionality of the polyhedron was most apparent. Due to the nature of the raster graphics hardware used it was very slow while drawing the polyhedron but once drawn the shades of the individual triangles could be changed very fast. The trackball was used to input changes in x-y angles for the location of the light source from the center of the screen. The apparent light source on the polyhedron could be changed rapidly by recalculating all the new shades for each triangle and sending them to the display. The shades could be changed fast enough that the light source could be moved almost in real time, (about 200 milliseconds to change a polyhedron with 50 exposed facets). This progressively changing light source brought out 3-dimensionality very well.

Using raster graphics to display polyhedra can make them look very natural from a human point of view. They can even be made somewhat dynamic by moving the light source. However it was impractical to rotate the picture in real time with the equipment available.

Fig. 7.3 Example of Polyhedron Shown on Raster Display

CHAPTER 8: EVALUATION

8.1 Number of Points to Make a Picture

The quality of a picture consisting of points in space depends very much on the density of points in the picture. If too many points were shown, the picture would be white and nothing could be seen. Too few points, and the picture would convey nothing. Somewhere in between is a region where there are just enough points to describe what is required to be seen.

Presumably the minimum number of points is dependent on the number of distinguishing features to be shown in the picture. A distinguishing feature could be any simple surface section of the object to be investigated. These features would have somewhat rounded profiles and would be either flat planes or slightly curved planes. Any features with sharp edges would have to be broken into smaller more-rounded features. As an example, a cube could consist of six distinguishing features, one for each of its sides. A sphere could consist of just one curved feature, or perhaps it should consist of several features to reduce the total angular change per feature. There is no correct answer, but it is required that a degree of magnitude be found for the amount of points required to describe an object. As a test, the number of points needed to describe one side of a cube and the number needed to describe the

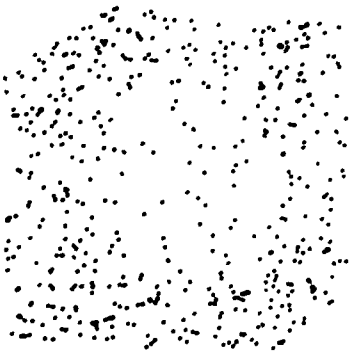
surface of a sphere were estimated and compared to get an upper and lower bound for the number of points required to describe a "feature".

Figures 8.1 thru 8.4 show how recognizable a cube and a sphere can be made with different point densities for dot and polyhedron displays. It can be seen that a cube described by points does not become recognizable until there are at least 500 points on the cube. Although it cannot be shown here, the cube became recognizable with only 200 points if it was rotated on the screen. The sphere became apparent with only 100 points rotated or not. Perhaps this was because a sphere looks the same from any view. A cube shown with the points connected into a polyhedron became fairly recognizable with only 50 random points. It must be kept in mind though that 8 well placed points can perfectly describe a cube. The sphere still needed about 100 points to look like a sphere even when the points were connected. This may be because the curved lines of a sphere are not suited for description by the straight edges of a polyhedron.

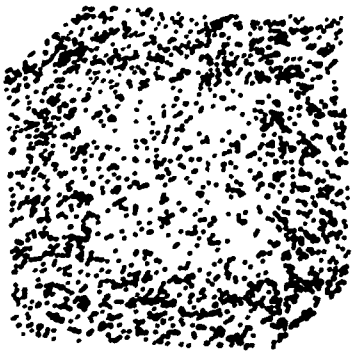
Since a cube requires 500 random points to describe its surface, then 85 points are required to describe one of its six distinguishing features. A sphere still requires 100 points, assuming it consists of only one feature. For polyhedrons, a cube feature needs about 20 points and a sphere requires 100. It will be assumed here that all

20 Points

100 Points

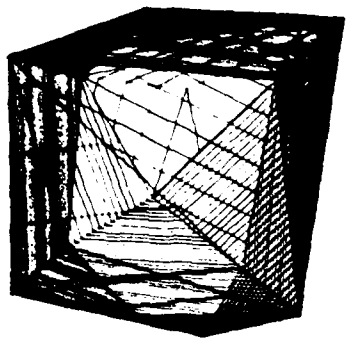


500 Points

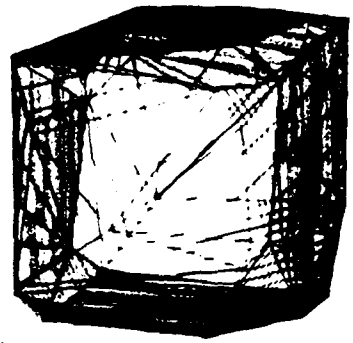


2000 Points

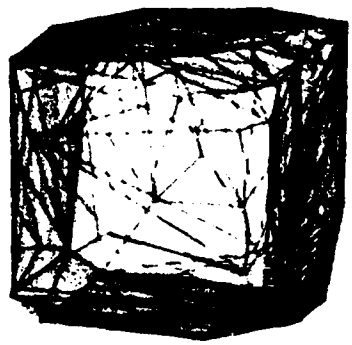
Fig. 8.1 Cubes Described by Randomly Distributed Points



20 Points

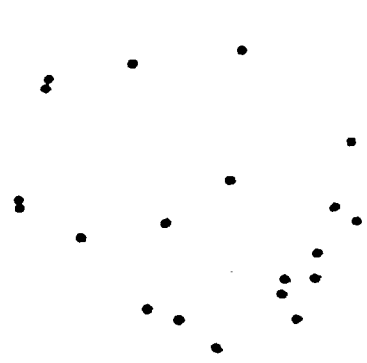


50 Points

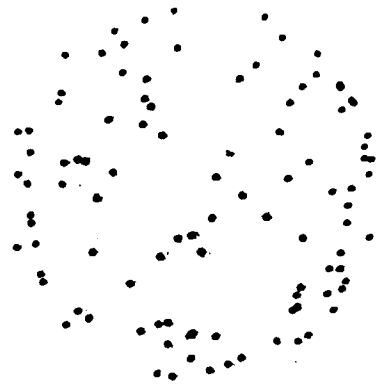


100 Points

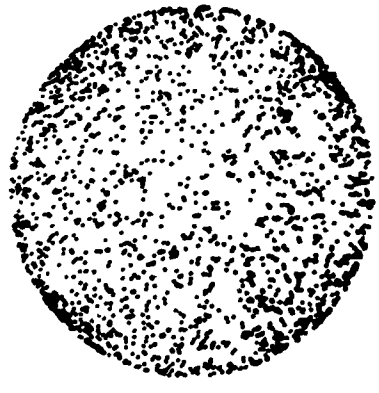
Fig. 8.2 Random Cube Points Made Into Polyhedron



20 Points

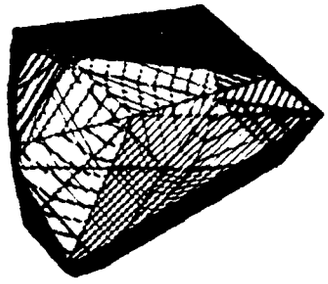


100 Points

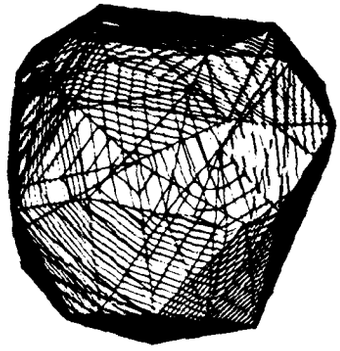


2000 Points

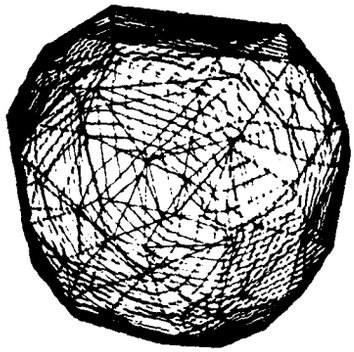
Fig. 8.3 Spheres Described by Randomly Distributed Points



20 Points



50 Points



100 Points

Fig. 8.4 Random Sphere Points Made Into Polyhedron

distinguishing features on any object require about the same amount of randomly distributed points to define its shape for a human. Different sized features would also require the same amount of points, they would just have different point densities.

Any object can be broken into arbitrarily small features depending on the degree of detail required. Say an area in front of a manipulator must be completely described by touch points and it is necessary that all features down to three inches across must be recognizable. This means the entire area must be covered with a point density sufficient to describe a 3 inch feature. If the area to be investigated is 20 square feet and a suface feature is assumed to require 100 points to be well described, then the entire area would have to be covered with 32000 points to describe all features down to 3 inches across. If the points are to be connected into polyhedrons, then it can be assumed that only 20 points are needed per feature, 6400 points will be required to cover the entire area.

The above figures are probably exaggerated because the manipulator operator is allowed to choose where he wants to put a high concentration of points. He can leave some areas with very few points if he decides they are unimportant. Also, if the picture can be rotated, the number of required points can be greatly reduced.

A problem unique to points that were connected into

polyhedrons was that the surface of the polyhedron could become degraded if the points were too densily packed together. That is, if the points were closer together than the positioning error of the manipulator, then lines connected between them would not likely lay parallel to the actual surface. These points would make a very jagged surface on a polyhedron. One solution would be to delete points that are to close to other points. This will not reduce the resolution because it is already limited by the manipulator accuracy.

8.2 Speed of Picture Construction

8.2.1 Constuction Time for Points

The amount of time required to read points from the touch sensor and then draw them on the display was very short. When using a single touch sensor switch, one point could be read in at every cycle of the program. One cycle took about 20 milliseconds so conceivably 50 points could be read within one second. The computer could read points even faster with the brush sensor because it had 10 switches. The limiting factor was not how fast computer could read points but the speed the touch sensor could respond. The single touch sensor could not be moved fast enough to read more than 2 or 3 points per second and the brush sensor was not much faster because, although it could read many points

at once, it was more cumbersome to maneuver.

Clearly, a touch sensor is required that can read points very rapidly if a picture of a manipulator's surroundings is to be made in a reasonable amount of time. A fast touch sensor could be made if it had many switches and if it was set up such that the switches did not interfere with one another, (see Chap. 2). This type of sensor would be considerably more expensive than the ones used in this project but would probably be worth it for the amount of time that would be saved. Another way to increase speed would be to make a sensor that could stream points in without having to lift off the surface for every point. A streaming sensor would work best if it was non-rigidly mounted to the manipulator . That way the manipulator would not have to follow every bend and corner encountered on the surface.

As an example, assume the maximum point coordinate reading rate of the computer is 200 points per second. If a touch sensor was built with 20 switches on it, then the computer would be capable of reading 10 points per second per switch. This rate would not be unreasonable if the switches were made to stream points in. A touch sensor capable of reading points at 200 per second could essentially cover any surface encountered with a thick mat of points in a very short time.

8.2.2 Construction Time for Polyhedra

The speed of the computer was the limiting factor for construction of polyhedra. The time period required to attach a new point went up with the number of facets on the polyhedron. Fig. 8.5 shows a graph of average time required to attach a new point versus the number of points in the polyhedron for the computer program in Appendix B.

There are many areas of this program that could be made to run much faster at the expense of more program complexity. To attach a new point, the program had to test every facet of the polyhedron for suitability. This was very time consuming. For this reason a condition was added that the computer only make complete tests on the five facets with nearest centroids to the new point. This condition increased the speed of the program by a factor of two. Other parts of the program could have used this same kind of selectivity. For example, after a facet was chosen for attachment, all the other facets had to be checked to see that they did not get in the way. Also, all the facets and all the touch vectors had to be checked for interference before a pair of facets could be changed. These checks significantly slowed computation.

Perhaps the thing that contributed most to slowing the program was the basic philosophy that points should be attached to the polyhedron in the order they were found by the operator. If all the points could be known at the start

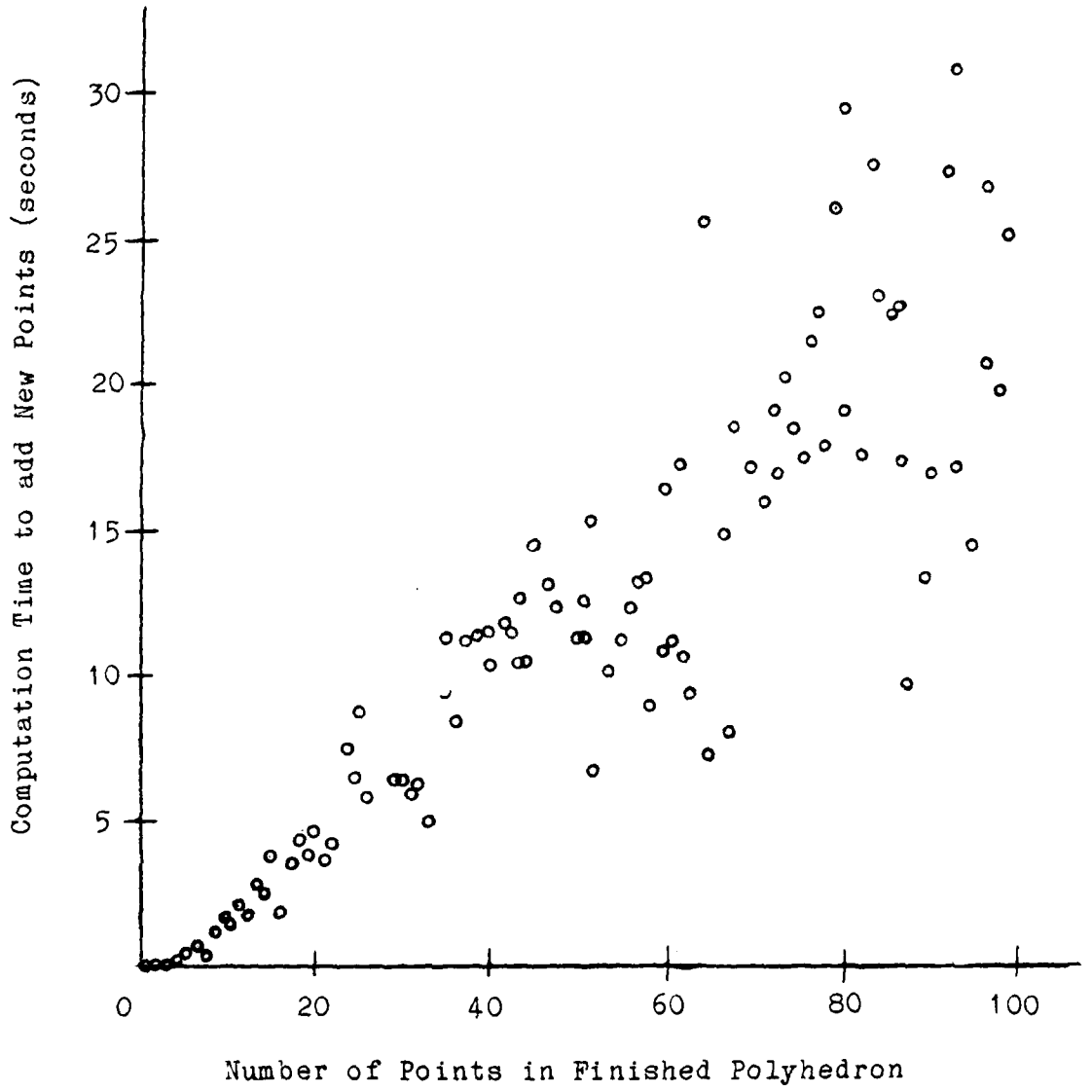


Fig. 8.5 Graph of Computation Time Versus Polyhedron Size

and arranged in the best sequence for attachment, many of these extensive comparisions and checks might be eliminated. This might also allow the points to be seperated into small groups and connected together in patches to further increase speed.

8.3 Raster Display

Drawing a picture of the polyhedron on the raster display was much slower than any other method tested. One facet of the polyhedron could be drawn on the display in about half a second so real-time rotation of the picture was impossible. Raster graphic hardware is available on the market that will draw a picture much faster but can be very complex. The raster display was best used for making permanent pictures because it was capable of making them look very realistic.

CHAPTER 9 CONCLUSIONS AND RECOMENDATIONS

9.1 Conclusions

This project has shown that a supervisory controlled manipulator can be used to construct an understandable 3-dimensional picture of its surroundings with just the sense of touch. The picture can consist simply of surface points shown on a computer graphic display. It is also shown how a more sophisticated picture can be made by reconstructing a surface from these points. Not only can a picture be made that is recognizable to a human, 3-D surface data that is easily digestable by a computer is also provided.

In situations where vision of the manipulstor work area by the operator is difficult or impossible, these methods of touch sensor picture construction could be a good aid or replacement for the usual television camera.

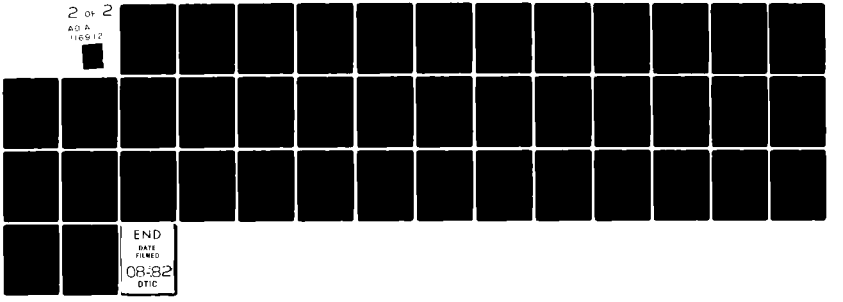
9.2 Recomendations

A touch sensor would have to be developed that could sense points very rapidly for touch generated pictures to be of practical use. That way a picture could be essentially "painted" with the sensor. Also the surface construction program would have to be made to go faster to be able to use it in real-time. This should not be impossible as the number of required calculations to attach each point to the

AD-A116 912 MASSACHUSETTS INST OF TECH CAMBRIDGE MAN-MACHINE SYS--ETC F/G 17/8
COMPUTER GRAPHIC REPRESENTATION OF REMOTE ENVIRONMENT USING POS--ETC(U)
AUG 81 D C FYLER N00014-77-C-0256

UNCLASSIFIED NL

2 OF 2
AD A 116912



END
DATE FILMED
08-82
DTIC

CHAPTER 9 CONCLUSIONS AND RECOMENDATIONS

9.1 Conclusions

This project has shown that a supervisory controlled manipulator can be used to construct an understandable 3-dimensional picture of its surroundings with just the sense of touch. The picture can consist simply of surface points shown on a computer graphic display. It is also shown how a more sophisticated picture can be made by reconstructing a surface from these points. Not only can a picture be made that is recognizable to a human, 3-D surface data that is easily digestable by a computer is also provided.

In situations where vision of the manipulstor work area by the operator is difficult or impossible, these methods of touch sensor picture construction could be a good aid or replacement for the usual television camera.

9.2 Recomendations

A touch sensor would have to be developed that could sense points very rapidly for touch generated pictures to be of practical use. That way a picture could be essentially "painted" with the sensor. Also the surface construction program would have to be made to go faster to be able to use it in real-time. This should not be impossible as the number of required calculations to attach each point to the

polyhedron can be held to a maximum value.

There are many aspects of surface construction from points that could use further study:

1.) A method is needed to decide if there should be more than one polyhedron or surface in front of the manipulator. This in turn leads to the problem of attaching or detaching different polyhedra from each other.

2.) An interesting problem would be to find a method to construct polyhedra with holes passing through them. A polyhedron with a hole does not follow Euler's Formula.

3.) No allowance was made in this study for a moving object. If the motion were known then there ought to be a way to compensate for this in the construction on the screen.

REFERENCES

1.) C.M.Winey, "Computer Simulated Visual and Tactile Feedback as an Aid to Manipulator and Vehicle Control", Masters Thesis, MIT, 1981.

2.) K.Tani, "Supervisory Control of Remote Manipulation with Compensation for Moving Target", Report for Man-Machine Systems Laboratory, MIT, 1980.

3.) T.L.Brooks, "Superman: A System for Supervisory Manipulation and the Study of Human/Computer Interactions", Masters Thesis, MIT, 1979.

4.) T.B.Sheridan, W.L.Verplank, "Human and Computer Control of Undersea Teleoperators", Man-Machine Systems Laboratory Report, MIT, 1979.

5.) L.D.Harmon, "The Sense of Touch Begins to Gather Momentum", Sensor Review, April 1981, 81-89.

6.) D.D.Grossman, R.H.Taylor, "Interactive Generation of Object Models with a Manipulator", IEEE Transactions on Systems, Man, and Cybernetics, Vol SMC-8, Sept 1978.

7.) W.M.Newman, R.F.Sproull, "Principles of Interactive Computer Graphics", McGraw-Hill, 2nd Ed, 1979.

8.) C.T. Zahn, "Graph-Theoretical Methods for Detecting and Describing Gestalt Clusters", IEEE Trans. Comput. C-20, 1971, 68-86.

9.) G. Gini, M.Gini, "Object Description with a Manipulator", The Industrial Robot, March 1978.

APPENDIX I.

COMPUTER PROGRAM DESCRIPTION

Interdependent tasks such as manipulator simulation, vector graphic display, and polyhedron construction where all combined in one Fortran 4-Plus program because it was most practical that they all work at the same time. Raster graphic display was done on a seperate program as it did not have to run in real-time.

MAIN PROGRAM

The main program, TOUCH, handled manipulator simulation, touch sensing, and program initialization. TOUCH was basicly a stripped down version of C. Winey's ARM program [1]. Only those parts that were required for manipulator simulation were saved because cycle time was critical. The touch sensing capability was added and took care of locating points and touch vectors any time a touch sensor switch was found to be tripped. Also some algorithms were added to improve absolute point coordinate calculation as described in Chapter 5.

When running, the processor would simply loop through TOUCH continually refreshing the manipulator display and waiting for an outside command. Control would be transfered to subroutine DISP in the event of a keyboard input or to

subroutine CON if a touch sensor tripped when a polyhedron was being constructed. Cycle time through TOUCH was about 20 milliseconds which was fast enough to simulate a smooth moving manipulator and give it a reasonably good reaction time to respond to touch inputs.

Subroutine DISP responded to any keyboard inputs and took care of display managment. It controlled view angle, set program parameters, and organized information output. It was responsible for creating, deleting, and starting construction of polyhedra. DISP was called every cycle of TOUCH when it was required that the display be dynamicly rotated or moved. This increased cycle time to 26 milliseconds.

Subroutine CON took care of adding new points to an existing polyhedron. If no polyhedron existed, CON would do the process of initialization described in Chapter 6. CON decided which was the best facet to attach to and made sure that it did not violate any rules for a closed polyhedra. After the point was attached CON did the job of deciding which facet pairs to check for smoothing.

Subroutine FACE compared facet pairs and decided when they should be switched with compliment facets. It determined the angles between neighboring facets and checked that new facets did not violate any rules for closed polyhedra. FACE was be called by CON when checking facet pairs and could also be called by DISP when the operator

wanted to check or change facets from the keyboard.

Subroutine CTOUR drew evenly spaced contour lines across the existing polyhedron. These contour lines were always drawn on the object coordinate z plane.

Subroutine JROL performed rotations in screen coordinates for control by the joystick or trackball.

The following list of subroutines took care of individual tasks that were often required by main subroutines.

Subroutine PIERC compared relationships between a line and a triangle. It determined if the line pierced through the triangle, if the triangle faced away from the base of the line, and if the line pointed away from the triangle. It could also determine the distance along the direction of the line from the base of the line to the plane described by the triangle. PIERC was used to determine if two facets were concave or convex, if a touch vector was at an angle greater than 90 degrees to a facet, or if a line segment stuck through a facet.

CROSS - determined the normal vector of a plane described by three points in 3-space.

ANGL - determined the angle difference between two vectors in 3-space.

SEARCH - found the third point of a facet on an existing polyhedron if given the two other points in sequence for

that facet.

VECT - drew a line on the screen between two specified touch points.

The following are the set of library subroutines that were used to control the vector graphics display processor:

MGINIT -initialize the Megatek

MGSEND -send data in display buffer to Megatek

SETINT -set the light intensity for all lines drawn after it

DRWI3 -draw a 3-D line

MOVI3 -move to a new 3-D location without drawing line

PNTI3 -draw a point in 3-D

NPOINT -find last line number being used by Megatek

MODIFY -modify next command in Megatek with next call

LDPTRO -reset beginning of Megatek display and erase everything after it

LDTRN3 -send transformation coefficients for rotation, translation, and zoom for all lines drawn after it

RASTER DISPLAY

The program DRW read 3-dimensional points and polyhedron data from a data file from DISP. The points were preformatted on the vector graphic display. DRW drew all the facets facing toward the screen on the Lexidata. Furthermost facets were drawn first so that they would be

erased if a closer facet was in front of them. Shading was accomplished by relating a facet to the angle between a facet normal and a vector simulating a light source direction. The light source direction could be changed with a trackball very quickly by changing the shading lookup table.

The following are a list of subroutines used to read the trackball and control the Lexidata:

TBALL - read trackball x and y velocities and the combined value of three switches.

DSVEC - drew a line between two points and selected a shading lookup number.

DSLLU - changed the shade of one lookup number.

DSLWT - changed the shades of many lookup number according to an array.

APPENDIX B1. COMPUTER PROGRAM FOR DISPLAY OF MANIPULATOR AND SURFACE POINTS

```
      PROGRAM TOUCH
C INITIALIZE PROGRAM
      DIMENSION IPT(4),XX(4),XY(4),XZ(4),XT(4),YX(4),YY(4)
      DIMENSION YZ(4),ZX(4),ZY(4),ZZ(4),YT(4),ZT(4)
      DIMENSION SCL(7,2),IA(16),A(7)
      DIMENSION IOSB(2),IBUF(12),IPOT(10),MS(10),IPARAM(6)
      COMMON /DMABUF/ IDUM(2298),ADAT(51,3),BRP(36,3),
     1 ICON(90,2),IBRC(50,2),IFC(200,3),M(100,3)
      COMMON /FACT/IFMAX,NX(30),NA,IPS NCON,NPOL,ICCN,
     1 IVECT,ISUP,IRX
      COMMON /IPTPS/ IANG(100,2),ICHECK,VEX
      COMMON /DISPL/ICM,XXD,XYD,XZD,XTD,YXD,YYD,YZD,
     1 YTD,ZXD,ZYD,ZZD,ISHAD,IARM,IWALL,IROLL,JSTICK,IDOTR
C INITIALIZE THE MEGATEK AND A/D
      CALL ANINIT
      CALL MGINIT
      CALL SETINT(13)
      CALL NPOINT(IREP)
C INITIALIZE THE KEYBOARD MONITER ROUTINE
      CALL GETADR(IPARAM(1),ICMD)
      IPARAM(2)=1
      IEXC="033
      LLL="114
      IAAA="101
C INITIALIZE VIEW AND MENU
100   IRX=-5
      CALL DISP
      IRX=0
      ICM="114
      CALL DISP
C SET LINK LENGTHS AND ORIGIN
      AY=55.625
      AZ=1600.
      SZ=720.
      ZOG=480.
      YOG=960.
      VEX=2
C READ SCALING FACTORS FOR A/D OUTPUT OF ANGLES
      OPEN(UNIT=4,NAME='SCALE.DAT',TYPE='OLD')
      READ(4,*)((SCL(I,J),J=1,2),I=1,7)
      CLOSE(UNIT=4,DISPOSE='SAVE')
C READ POINT DATA FOR MANIPULATOR
      OPEN(UNIT=4,NAME='ARMSDT.DAT',TYPE='OLD')
      DO 101 I=1,60
      READ(4,*,END=102)ADAT(I,1),ADAT(I,2),ADAT(I,3)
101   CONTINUE
102   CLOSE(UNIT=4,DISPOSE='SAVE')
C READ CONNECTIVITY DATA FOR MANIPULATOR
      OPEN(UNIT=4,NAME='ARMSCN.DAT',TYPE='OLD')
      DO 103 I=1,100
```

```
        READ(4,*,END=104)ICON(I,1),ICON(I,2)
103     CONTINUE
104     CLOSE(UNIT=4,DISPOSE='SAVE')
C READ POINT DATA FOR TOUCH SENSOR
        OPEN(UNIT=4,NAME='BRSHDT.DAT',TYPE ='OLD')
        DO 105 I=1,50
        READ(4,*,END=106)BRP(I,1),BRP(I,2),BRP(I,3)
105     CONTINUE
106     CLOSE(UNIT=4,DISPOSE='SAVE')
C READ CONNECTIVITY DATA FOR TOUCH SENSOR
        OPEN(UNIT=4,NAME='BRSHCN.DAT',TYPE='OLD')
        DO 107 I=1,50
        READ(4,*,END=108)IBRC(I,1),IBRC(I,2)
        NBCON=I
107     CONTINUE
108     CLOSE(UNIT=4,DISPOSE='SAVE')
C INPUT ARM AND WALL LINES INTO MEGATEK
        IXXX=83+NBCON
        DO 128 I=1,IXXX
        INK=I-NBCON
        IF(I.EQ.1)GOTO 341
        IF(INK.EQ.36)GOTO 343
        IF(INK.EQ.56)GOTO 342
        IF(INK.EQ.72)GOTO 344
        GOTO 346
C INPUT TOUCH SENSOR
341     CALL SETINT(13)
        CALL NPOINT(IPT(2))
        IARM=IPT(2)-1
        GOTO 345
C INPUT SHOULDER
342     CALL NPOINT(IPT(3))
        GOTO 345
C INPUT FOREARM
343     CALL NPOINT(IPT(4))
        GOTO 345
C INPUT WALLS
344     CALL SETINT(13)
        CALL NPOINT(IPT(1))
        IWALL=IPT(1)-1
345     CALL LDTRN3(1.,0.,0.,3000.,0.,1.,0.,0.)
346     IF(INK.LE.0)GOTO 250
        MR=ICON(INK,1)
        MM=ICON(INK,2)
        IX1=40.*ADAT(MR,1)
        IX2=40.*ADAT(MM,1)
        IY1=40.*ADAT(MR,2)
        IY2=40.*ADAT(MM,2)
        IZ1=40.*ADAT(MR,3)
        IZ2=40.*ADAT(MM,3)
        GOTO 249
250     MR=IBRC(I,1)
```

```
        MM=IBRC(I,2)
        IX1=40.*BRP(MR,1)
        IX2=40.*BRP(MM,1)
        IY1=40.*BRP(MR,2)
        IY2=40.*BRP(MM,2)
        IZ1=40.*BRP(MR,3)
        IZ2=40.*BRP(MM,3)
        IF(IX1.EQ.880.OR.IX2.EQ.880)GOTO 128
249     CALL MOVI3(IX1,IY1,IZ1)
        CALL DRWI3(IX2,IY2,IZ2)
C SEND TO DISPLAY
        CALL MGSEND
128     CONTINUE
129     CONTINUE
C SET DISPLAY AFTER MANIPULATOR
        CALL SETINT(13)
        CALL NPOINT(NCON)
        CALL MGSEND
C READ ARM POSITION FROM A/D CONVERTER AND CONVERT TO
VOLTAGE
C READ TOUCH SENSOR SWITCHES
112     CALL AINSQ(16,22,IA)
        CALL DIN(20,ISP)
135     DO 113 I=1,7
        A(I)=FLOAT(IA(I))/3276.2
113     CONTINUE
C SCALE A/D OUTPUT, FILTER, AND CALCULATE SINES _COSINES
914     THZ=SCL(1,1)*A(5)+SCL(1,2)
        THX=SCL(2,1)*A(7)+SCL(2,2)
        THYZ=SCL(3,1)*A(6)+SCL(3,2)
        THY=THYZ-THZ
        THA=SCL(4,1)*A(2)+SCL(4,2)
        THR=SCL(5,1)*A(3)+SCL(5,2)
        THL=SCL(6,1)*A(4)+SCL(6,2)
        S1=SIN(THZ)
        S2=SIN(THX)
        S4=SIN(THA)
        C1=COS(THZ)
        C2=COS(THX)
        C4=COS(THA)
C PREFORM PUSHROD CALCULATION
        ZP1=-2.25*S2-4.5*C2*CP3
        XGXP=3.1-2.25*C2+4.5*S2*CP3
        ZGZP=-4.5*COS(THY)+2.25*S2+4.5*C2*CP3
        YP=4.5*SIN(THY)+SQRT(324.72-XGXP*XGXP-ZGZP*ZGZP)
        SP3=(YP-18.)/4.5
        THY1=ASIN(SP3)
        CP3=COS(THY1)
C ROTATE JOINT 90 DEGREES
        S3=-CP3
        C3=SP3
C PREFORM DIFFERENTIAL CALCULATION
```

```
      S5=SIN((THR+THL)/2)
      S6=SIN((THL-THR)/1.65)
      C5=COS((THR+THL)/2)
      C6=COS((THL-THR)/1.65)
C DO LINK TRANSFORMATIONS
C SHOULDER TRANSFORMS
      XX(3)=C2
      XY(3)=-S2
      YX(3)=C1*S2
      YY(3)=C1*C2
      YZ(3)=-S1
      YT(3)=YOG
      ZX(3)=S2*S1
      ZY(3)=S1*C2
      ZZ(3)=C1
      ZT(3)=ZOG
C FOREARM TRANSFORMATIONS
      XX(4)=C2*C4-S2*C3*S4
      XY(4)=-C2*S4-S2*C3*C4
      XZ(4)=S2*S3
      YX(4)=C1*S2*C4+C1*C2*C3*S4-S1*S3*S4
      YY(4)=-C1*S2*S4+C1*C2*C3*C4-S1*S3*C4
      YZ(4)=-C1*C2*S3-S1*C3
      YT(4)=S1*S2+YOG
      ZX(4)=S1*S2*C4+S1*C2*C3*S4+C1*S3*S4
      ZY(4)=-S1*S2*S4+S1*C2*C3*C4+C1*S3*C4
      ZZ(4)=-S1*C2*S3+C1*C3
      ZT(4)=-C1*SZ+ZOG
C HAND TRANSFORMATIONS
      XX(2)=XX(4)*C6+XY(4)*C5*S6+XZ(4)*S5*S6
      XY(2)=-XX(4)*S6+XY(4)*C5*C6+XZ(4)*S5*C6
      XZ(2)=-XY(4)*S5+XZ(4)*C5
      XT(2)=-XZ(4)*AZ+XY(4)*AY
      YX(2)=YX(4)*C6+YY(4)*C5*S6+YZ(4)*S5*S6
      YY(2)=-YX(4)*S6+YY(4)*C5*C6+YZ(4)*S5*C6
      YZ(2)=-YY(4)*S5+YZ(4)*C5
      YT(2)=-YZ(4)*AZ+YT(4)+YY(4)*AY
      ZX(2)=ZX(4)*C6+ZY(4)*C5*S6+ZZ(4)*S5*S6
      ZY(2)=-ZX(4)*S6+ZY(4)*C5*C6+ZZ(4)*S5*C6
      ZZ(2)=-ZY(4)*S5+ZZ(4)*C5
      ZT(2)=-ZZ(4)*AZ+ZT(4)+ZY(4)*AY
C
C DO DISPLAY TRANSFORM AND SEND TO DISPLAY
      DO 371 I=2,4
60    XX1=XX(I)*XXD+YX(I)*XYD+ZX(I)*XZD
      XY1=XY(I)*XXD+YY(I)*XYD+ZY(I)*XZD
      XZ1=XZ(I)*XXD+YZ(I)*XYD+ZZ(I)*XZD
      XT1=XT(I)*XXD+YT(I)*XYD+ZT(I)*XZD+XTD
      YX1=XX(I)*YXD+YX(I)*YYD+ZX(I)*YZD
      YY1=XY(I)*YXD+YY(I)*YYD+ZY(I)*YZD
      YZ1=XZ(I)*YXD+YZ(I)*YYD+ZZ(I)*YZD
      YT1=XT(I)*YXD+YT(I)*YYD+ZT(I)*YZD+YTD
```

```
        CALL MODIFY(IPT(I))
        CALL LDTRN3(XX1,XY1,XZ1,XT1,YX1,YY1,YZ1,YT1)
371     CONTINUE
C DO WALL TRANSFORMATION
        CALL MODIFY(IPT(1))
        CALL LDTRN3(XXD,XYD,XZD,XTD,YXD,YYD,YZD,YTD)
C
C EXAMINE TOUCH SENSOR SWITCHES
        IF(ISP.EQ."177777)GOTO 372
62      DO 372 I=1,10
        J=2**(I-1)
C PUT WAIT LIMIT ON SWITCHES OF 4 CYCLES
        IF((ISP.AND.J).EQ.0)IPOT(I)=1
        IF(IPOT(I).EQ.0.AND.MS(I).GT.0)MS(I)=MS(I)-1
        IF(IPOT(I).EQ.0.OR.MS(I).NE.0)GOTO 373
        MS(I)=4
C RING TERMINAL BELL IF QIO IS OFF
        NBEEP="007
        IF(IRX.EQ.-4)WRITE(5,765)NBEEP
765     FORMAT(' ',1A1)
C INCREMENT POINT COUNTER
        IPS=IPS+1
C FIND SENSOR CENTERLINE
        XP=BRP(I,1)*40.
        YP=BRP(I,2)*40.
        ZP=BRP(I,3)*40.
        XB=BRP(I+10,1)*40.
        YB=BRP(I+10,2)*40
        ZB=BRP(I+10,3)*40.
C DO TRANSFORM TO GET TOUCH POINT AND VECTOR IN
C MANIPULATOR COORDINATES
        MMMX=XP*XX(2)+YP*XY(2)+ZP*XZ(2)+XT(2)
        MMMY=XP*YX(2)+YP*YY(2)+ZP*YZ(2)+YT(2)
        MMMZ=XP*ZX(2)+YP*ZY(2)+ZP*ZZ(2)+ZT(2)
        XBT=XB*XX(2)+YB*XY(2)+ZB*XZ(2)+XT(2)
        YBT=XB*YX(2)+YB*YY(2)+ZB*YZ(2)+YT(2)
        ZBT=XB*ZX(2)+YB*ZY(2)+ZB*ZZ(2)+ZT(2)
        IF(IDOTR.EQ.1)WRITE(2,*)MMMX,MMMY,MMMZ
        IF(IPS.GT.100)GOTO 374
C POINT COORDINATES
        M(IPS,1)=MMMX
        M(IPS,2)=MMMY
        M(IPS,3)=MMMZ
C TOUCH VECTOR ANGLES *10000 (TO STORE AS INTEGERS)
        VL=SQRT((M(IPS,1)-XBT)**2+(M(IPS,2)-YBT)**2)
        IANG(IPS,1)=ATAN2(YBT-M(IPS,2),XBT-M(IPS,1))*10000.
        IANG(IPS,2)=ATAN2(ZBT-M(IPS,3),VL)*10000.
C DO CONNECTION IF ENABLED
        IF(ICCN.NE.1)GOTO 374
        TIME= SECNDS(0.0)
        CALL CON
        TIME=SECNDS(TIME)
```

```
        IF(IRX.EQ.-4)TYPE *,IPS,TIME
C RING BELL TO INDICATE COMPLETION
        IF(IRX.EQ.-4)WRITE(5,765)NBEEP
        GOTO 373
C DRAW POINT ON SCREEN
374     CALL PNTI3(MMMX,MMMY,MMMZ)
        CALL MGSEND
373     IPOT(I)=0
372     CONTINUE
C ENABLE QIO IF ARM IS TWISTED
        IF(IRX.EQ.-4.AND.THA.GT.3.0)IRX=0
        IF(IRX.EQ.-4)GOTO 112
C CHANGE DISPLAY TRANSFORMATIONS IF VIEW IS CHANGING
        IF(IROLL.EQ.1)CALL DISP
        IF(IVECT.EQ.2)GOTO 112
C READ KEYBOARD
        IF(IFF.NE.1)CALL QIO("10400,5,3,,IOSB,IPARAM,IDS)
        IFF=1
        CALL READEF(3,IUU)
        IF(IUU.NE.2)GOTO 112
        ICM=ICMD
        WRITE(5,999)IEXC,LLL,IEXC,IAAA
999     FORMAT('+',4A)
        IFF=0
        CALL DISP
        ICM=0
C LOOK AT DISPLAY FLAG
382     IF(IRX.EQ.-1)CALL LDPTRO(NCON)
        IF(IRX.EQ.-1)CALL MGSEND
        IF(IRX.EQ.-2)GOTO 100
        GOTO 112
        END
```

APPENDIX C. SUBROUTINES TO CONSTRUCT A POLYHEDRON FROM SURFACE POINT DATA

```
      SUBROUTINE CON
      COMMON /DMABUF/ IDUM(3060),NF(20),ID(20),
     1  IFC(200,3),M(100,3)
      COMMON /IPTPS/IANG(100,2)
      COMMON /FACT/IFMAX,NX(30),NA,IPS,NCON,NPOL,ICCN,
     1  IVECT,ISUP,IRX
C INITIALIZE VARIABLES
      NDIST=10  ! MAXIMUM DISTANCE TO FACET CENTROID
      NMAX=5    ! NUMBER OF FACETS FOR COMPLETE CHECKS
357   IPRC1=0
      PD1=0
      DL1=0
      IB=0
      ITRY=0
      NFMX=NMAX
      PI=3.1415927
      IF (IPS.GT.3)GOTO 3  !IPS=CURRENT NUMBER OF POINTS
      IF (IPS.GT.1)GOTO 1
C DRAW DOT FOR FIRST POINT
      CALL PNTI3(M(1,1),M(1,2),M(1,3))
      GOTO 5
1     IF (IPS.GT.2)GOTO 2
C DRAW LINE BETWEEN FIRST 2 POINTS
      CALL VECT(1,2)
      GOTO 5
C CONSTRUCT INITIALIZING FACETS ON FIRST 3 POINTS
2     CALL VECT(2,3)
      CALL VECT(3,1)
      IFC(1,1)=3   ! LOAD FIRST 2 FACETS FIRST 3 POINTS
      IFC(1,2)=2
      IFC(1,3)=1
      IFC(2,1)=1
      IFC(2,2)=2
      IFC(2,3)=3
      IFMAX=2  ! NUMBER OF FACETS ON EXISTING POLYHEDRON
5     CALL MGSEND
      RETURN
3     CONTINUE
      DO 320 I=1,20
      ID(I)=40.*NDIST
320   NF(I)=0
C FIND DISTANCE FROM POINT TO CENTROID OF ALL FACETS
      DO 321 I=1,IFMAX
      IFC1=IFC(I,1)
      IFC2=IFC(I,2)
      IFC3=IFC(I,3)
      FXA=(M(IFC1,1)+M(IFC2,1)+M(IFC3,1))/3.-M(IPS,1)
      FYA=(M(IFC1,2)+M(IFC2,2)+M(IFC3,2))/3.-M(IPS,2)
      FZA=(M(IFC1,3)+M(IFC2,3)+M(IFC3,3))/3.-M(IPS,3)
      LD=SQRT(FXA*FXA+FYA*FYA+FZA*FZA)
```

```
C ADD FACET TO LIST OF NEAREST FACETS IF CLOSE ENOUGH
        IF(LD.GE.ID(NMAX))GOTO 321
        ID(NMAX)=LD                ! DISTANCE TO NEAR FACET
        NF(NMAX)=I                 ! NUMBER OF NEAR FACET
        DO 322 J=1,NMAX-1
        J1=NMAX-J
        IF(LD.GE.ID(J1))GOTO 321
        ID(J1+1)=ID(J1)
        NF(J1+1)=NF(J1)
        ID(J1)=LD
        NF(J1)=I
322     CONTINUE
321     CONTINUE
C BEGIN SEARCH FOR BEST FACET
323     DO 100 IC=1,NFMX
        I=IC
        IF(ITRY.EQ.1)GOTO 324
        IF(NF(IC).LT.1.OR.NF(IC).GT.IFMAX)GOTO 100
        I=NF(IC)
C
324     IFC1=IFC(I,1)
        IFC2=IFC(I,2)
        IFC3=IFC(I,3)
        ICW=0    !SET FLAG TO SIGNIFY ORDINARY FACET CHECK
C
C FIND IF TOUCH VECTOR PIERCES FACET (IPEIRC)
C FIND WHICH WAY FACET IS FACING POINT (LOUTF)
C FIND DISTANCE BETWEEN POINT AND FACET PLANE ALONG
C TOUCH VECTOR (PDIST)
        CALL PIERC(IPS,IFC1,IFC2,IFC3,IPIERC,LOUTF,
     1  PDIST,ICW)
C
C DECIDE IF FACET IS BEST SO FAR
C
C CHECK IF DIRECTION VECTOR POINTS FOWARD THRU FACET
        IF (IPIERC.LE.0)GOTO 40
C
C REJECT POINT IF FACET FACES TOWARD TOUCH POINT
        IF (LOUTF.GE.0)GOTO 38
        IB=0
        TYPE *,'NEGATIVE PIERCING FACET'
        GOTO 52
C
C COMPARE TO BEST FACET
38      IF (IPRC1.LE.0.OR.PDIST.LT.PD1)GOTO 60
        GOTO 50
C
C REJECT ALL OTHER FACETS IF BEST IS PIERCED POSITVE
40      IF (INTPNT.EQ.1)GOTO 50
C
C CHECK CASE WHERE DIRECTION VECTOR POINTS AWAY THRU FACET
        IF (IPIERC.EQ.0)GOTO 45
```

```
        IF (PDIST.GT.0) GOTO 50
        IF (LOUTF.EQ.1)GOTO 50
        IF (IPRC1.EQ.0)GOTO 60
        IF (PDIST.LT.PD1)GOTO 50
        GOTO 60    ! GO FOR FURTHER TESTS
C CHECK CASE WHERE DIRECTION VECTOR DOESNT PIERCE FACET
45      IF (LOUTF.EQ.1)GOTO 50
        IF (IPRC1.NE.0)GOTO 50
C
C FIND DISTANCE TO CENTROID OF FACET
        FXA=(M(IFC1,1)+M(IFC2,1)+M(IFC3,1))/3.-M(IPS,1)
        FYA=(M(IFC1,2)+M(IFC2,2)+M(IFC3,2))/3.-M(IPS,2)
        FZA=(M(IFC1,3)+M(IFC2,3)+M(IFC3,3))/3.-M(IPS,3)
        DL=SQRT(FXA*FXA+FYA*FYA+FZA*FZA)
        IF (DL1.EQ.0)GOTO 60
        IF (DL1.LE.DL)GOTO 50 !REJECT IF NOT NEAREST SO FAR
C
C CHECK PIERCING OF OLD FACETS BY NEW LINES
60      DO 310 J=1,IFMAX
C SET FLAG TO CHECK PIERCING OF LINE SEGMENT THROUGH FACET
        ICWF=4
        CALL PIERC(IPS,IFC1,IFC(J,1),IFC(J,2),
     1  IFC(J,3),LOT,PDD,ICWF)
        IF(ICWF.EQ.6)GOTO 50
        CALL PIERC(IPS,IFC2,IFC(J,1),IFC(J,2),
     1  IFC(J,3),LOT,PDD,ICWF)
        IF(ICWF.EQ.6)GOTO 50
        CALL PIERC(IPS,IFC3,IFC(J,1),IFC(J,2),
     1  IFC(J,3),LOT,PDD,ICWF)
310     IF(ICWF.EQ.6)GOTO 50
C
C CHECK PIERCING OF NEW FACETS BY ALL OTHER TOUCH VECTORS
        DO 51 J=1,IPS
        ICWF=0
        IPP=0
        CALL PIERC(J,IPS,IFC2,IFC3,IPP,LOT,PDD,ICWF)
        IF(IPP.GT.0)GOTO 50
        CALL PIERC(J,IPS,IFC3,IFC1,IPP,LOT,PDD,ICWF)
        IF(IPP.GT.0)GOTO 50
        CALL PIERC(J,IPS,IFC1,IFC2,IPP,LOT,PDD,ICWF)
        IF(IPP.GT.0)GOTO 50
51      CONTINUE
C SAVE POINT AS BEST SO FAR AND SAVE ALL ITS ATTRIBUTES
        IF(IPIERC.EQ.0)DL1=DL
        PD1=PDIST
        IPRC1=IPIERC
        IB=I                ! NUMBER OF BEST FACET
50      CONTINUE
100     CONTINUE
C RETURN IF NO GOOD FACET IS FOUND
        IF(IB.EQ.0.AND.ITRY.EQ.0)GOTO 326
52      IF(IB.NE.0)GOTO 10
```

```
        IPS=IPS-1
        IF(IRX.EQ.-4)WRITE(5,234)
234     FORMAT('     *****REJECT POINT*****')
        RETURN
326     ITRY=1   ! MAKE SECOND TRY BY CHECKING ALL FACETS
        NFMX=IFMAX
        GOTO 323
C
C DRAW LINES FROM NEW POINT TO CHOSEN FACET
10      DO 55 I=1,3
55      CALL VECT(IPS,IFC(IB,I))
        CALL MGSEND
C
C GET RID OF OLD FACET AND ADD 3 NEW ONES
        IFC(IFMAX+1,1)=IPS
        IFC(IFMAX+2,1)=IPS
        IFC(IFMAX+1,2)=IFC(IB,2)
        IFC(IFMAX+2,2)=IFC(IB,3)
        IFC(IFMAX+1,3)=IFC(IB,3)
        IFC(IFMAX+2,3)=IFC(IB,1)
        IFC(IB,3)=IPS
        IFMAX=IFMAX+2
C
C  SELECT FACET PAIRS FOR CHECKING SMOOTHNESS
C
        DO 181 I=1,30
181     NX(I)=0              !LIST OF POINTS TO CHECK AROUND
        NX(1)=IPS
        NX(2)=IFC(IB,2)
        NX(3)=IFC(IB,3)
        NX(4)=IFC(IFMAX,2)
        NA=4
        NEND=0
140     IF(NA.GT.30)NA=30
        NX1=NX(NA)
        NA=NA-1
        K1=0
        DO 182 I=1,30
182     IF(NX1.EQ.NX(I))K1=K1+1
        IF(K1.GT.3)GOTO 143
        DO 141 I=1,IFMAX
        DO 142 J=1,3
        IF(NX1.NE.IFC(I,J))GOTO 142
        K1=NX1
        K2=IFC(I,1+MOD(J,3))
        CALL FACE(K1,K2)
        NEND=NEND+1
        IF(NEND.GT.50)GOTO 144
142     CONTINUE
141     CONTINUE
143     IF(NA.GT.0)GOTO 140
144     RETURN
```

```
        END
        SUBROUTINE FACE(K1,K2)
        DIMENSION IA(4)
        COMMON /DMABUF/ IDUM(3100),IFC(200,3),M(100,3)
        COMMON /FACT/ IFMAX,NX(30),NA,IPS,NCON,NPOL
        COMMON /IPTPS/ IANG(100,2),ICHECK,VEX,IFCC
C FIND ALTERNATE SET OF POINTS M1,M2
C       ISTICK=0                                !    INITIAL FACETS
        IFCC=0                                  !
        IF(K1.EQ.K2)RETURN                      !           M1
        IF(K1.EQ.0.OR.K2.EQ.0)RETURN            !            *
556     IF(K1.LT.K2)GOTO 5                      !           / \
        IFACE1=K1                               !          /   \
        K1=K2                                   !         /     \
        K2=IFACE1                               !    K1  *-------* K2
5       IFACE1=0                                !         \     /
        CALL SEARCH(K1,K2,M1,IFACE1)            !          \   /
        CALL SEARCH(K2,K1,M2,IFACE2)            !           \ /
        IF(M1.EQ.0.OR.M2.EQ.0)RETURN            !            *
70      IF(ICHECK.EQ.1)WRITE(5,*)K1,K2,M1,M2!       M2
        IF(M1.EQ.M2)RETURN                      !
        CALL SEARCH(M1,M2,J,I)                  !    OUT OF THE PAGE
        IF(J.NE.0)RETURN                        !    IS OUTSIDE THE
C IF ICHECK=2 FORCE FACET CHANGE                !    POLYHEDRON
        IF(ICHECK.EQ.2)GOTO 160
C
C FIND ATRIBUTES OF COMPLIMENT FACETS
90      CALL PIERC(K1,M1,M2,K2,IPRC3,LOUTF2,PDIST,ICW3)
        CALL PIERC(K2,M2,M1,K1,IPRC4,LOUTF3,PDIST,ICW4)
C IF ICHECK=1 THIS SUBROUTINE ONLY PRINTS THE FACET DATA
        IF(ICHECK.NE.1)GOTO 689
        TYPE *,'POINT  LOUTF  ICW  IPIERC'
        WRITE(5,*)K1,LOUTF2,ICW3,IPRC3
        WRITE(5,*)K2,LOUTF3,ICW4,IPRC4
689     IF(IPRC3.LE.0.AND.IPRC4.LE.0)GOTO 155
        ISTICK=1
        IF(LOUTF2.GT.0)RETURN
C
C
C CHECK IF TOUCH VECTOR AND FACET NORMAL ARE OVER
C 90 DEGREES APART
155     IF(ICW3.NE.1.AND.ICW4.NE.1)GOTO 159
        IF(LOUTF2.EQ.-1)RETURN
        GOTO 157
159     A1=0
        A2=0
C FIND THE 4 PERIPHERY POINTS
        CALL SEARCH(K1,M1,M11,I)
        CALL SEARCH(M1,K2,M12,I)
        CALL SEARCH(K2,M2,M22,I)
        CALL SEARCH(M2,K1,M21,I)
C FIND ALL THE SURFACE NORMALS
```

```
        CALL CROSS(K1,K2,M1,1)
        CALL CROSS(K2,K1,M2,2)
        CALL CROSS(M1,M2,K2,3)
        CALL CROSS(M2,M1,K1,4)
        CALL CROSS(K1,M1,M11,5)
        CALL CROSS(M1,K2,M12,6)
        CALL CROSS(K2,M2,M22,7)
        CALL CROSS(M2,K1,M21,8)
C FIND ANGLE BETWEEN ADJACENT FACETS AND ADD TOGETHER
        CALL ANGL(6,1,A1)
        CALL ANGL(7,2,A1)
        CALL ANGL(8,2,A1)
        CALL ANGL(5,1,A1)
        CALL ANGL(5,4,A2)
        CALL ANGL(6,3,A2)
        CALL ANGL(7,3,A2)
        CALL ANGL(8,4,A2)
        CALL ANGL(1,2,A1)
        CALL ANGL(3,4,A2)
420     IF(ICHECK.NE.1)GOTO 421
        TYPE *,'ORIGINAL ANGLE TOTAL=',A1
        TYPE *,'COMPLIMENT ANGLE TOTAL=',A2
421     IF(A1.LE.A2)RETURN
C
C CHECK IF NEW LINE PIERCES ANY FACETS
157     CALL PIERC(M1,K2,K1,M2,IPRC3,LOUTF1,PDIST,ICW3)
        CALL PIERC(M2,K1,K2,M1,IPRC4,LOUTF1,PDIST,ICW4)
        IF(ICHECK.NE.1)GOTO 156
        TYPE *,'POINT  LOUTF  ICW  IPIERC'
        WRITE(5,*)M1,LOUTF1,ICW3,IPRC3
        WRITE(5,*)M2,LOUTF1,ICW4,IPRC4
        RETURN
156     IF(IPRC3.LE.0.AND.IPRC4.LE.0)GOTO 158
        IF(LOUTF2.EQ.1)RETURN
158     IF((ICW3.EQ.1.OR.ICW4.EQ.1).AND.LOUTF2.EQ.-1)RETURN
        DO 160 I=1,IFMAX
        ICWF=4
        CALL PIERC(M1,M2,IFC(I,1),IFC(I,2),IFC(I,3),
     1  LOUTF1,PDIST,ICWF)
        IF(ICWF.EQ.6)RETURN
160     CONTINUE
C
C CHECK IF ANY LINES PIERCE NEW FACETS
        DO 568 I=1,IFMAX
        DO 569 J=1,3
        KK1=IFC(I,J)
        KK2=IFC(I,1+MOD(J,3))
        IF(KK1.GE.KK2)GOTO 569
        ICWF=4
        CALL PIERC(KK1,KK2,K1,M2,M1,LOUTF1,PDIST,ICWF)
        IF(ICWF.EQ.6)RETURN
        CALL PIERC(KK1,KK2,K2,M1,M2,LOUTF1,PDIST,ICWF)
```

```
        IF(ICWF.EQ.6)RETURN
569     CONTINUE
568     CONTINUE
C
C CHECK IF ANY TOUCH VECTORS PIERCE NEW FACETS
        IF(ISTICK.EQ.1)GOTO 570
        ICWF=0
        DO 570 I=1,IPS
        IF(I.EQ.K1.OR.I.EQ.K2.OR.I.EQ.M1.OR.I.EQ.M2)GOTO 570
        CALL PIERC(I,K1,M2,M1,IPRC1,LOUTF1,PDIST,ICWF)
        IF(IPRC1.EQ.0)GOTO 571
        IF(PDIST.GT.0)RETURN
571     CALL PIERC(I,K2,M1,M2,IPRC1,LOUTF1,PDIST,ICWF)
        IF(IPRC1.EQ.0)GOTO 570
        IF(PDIST.GT.0)RETURN
570     CONTINUE
        IFCC=1
C
C RECORD NEW FACETS
        IFC(IFACE1,1)=K1                !       CONVERTED FACETS
        IFC(IFACE1,2)=M2                !
        IFC(IFACE1,3)=M1                !              M1
        IFC(IFACE2,1)=K2                !               *
        IFC(IFACE2,2)=M1                !              /I\
        IFC(IFACE2,3)=M2                !             / I \
C                                       !            /  I  \
C  RECORD NEW LINES TO BE CHECKED       !        K1 *   I   * K2
        NA=NA+4                         !            \  I  /
        IF(NA.GT.30)GOTO 300            !             \ I /
        NX(30)=M1                       !              \I/
        NX(29)=M2                       !               *
        NX(28)=K1                       !              M2
        NX(27)=K2
        DO 161 J=1,4
        KK1=NX(30)
        DO 161 I=1,29
        KK2=NX(I)
        NX(I)=KK1
        KK1=NX(I+1)
        NX(I+1)=KK2
161     CONTINUE
C
C DRAW NEW POLYHEDROM
300     CALL LDPTRO(NCON)
        DO 310 I=1,IFMAX
        DO 309 J=1,3
        ILM1=IFC(I,J)
        ILM2=IFC(I,1+MOD(J,3))
        IF(ILM1.GT.ILM2)GOTO 308
        CALL VECT(ILM1,ILM2)
308     CONTINUE
309     CONTINUE
```

```
710     CONTINUE
        CALL MGSEND
        RETURN
        END
C               SUBROUTINE  PIERC
C THIS SUBROUTINE CALCULATES PARAMETERS BETWEEN A VECTOR AND
C A TRIANGLE.  IN TOUCH VECTOR MODE K1 IS THE TOUCH
C POINT NUMBER AND K1-K2-K3 IS INPUT CORNER POINTS OF THE
C TRIANGLE. IN THIS MODE ICW WILL BE OUTPUT AS 1 IF THE
C TRIANGLE KP-K1-K2 HAS A SURFACE NORMAL MORE THAN 90
C DEGREES FROM THE TOUCH VECTOR.
C IN LINE SEGMENT MODE, (ICW=4), KP IS INPUT AS THE PRIMARY
C ENDPOINT OF THE LINE SEGMENT AND K1 IS THE SECONDARY
C ENDPOINT AND K2-K3-K4 IS THE TRIANGLE.
C
C AS OUTPUT, K4=1 IF THE VECTOR PIERCES THE FACET ON THE
C POSITIVE SIDE OF THE FACET AND K4=-1 IF IT PIERCES FROM
C THE NEGATIVE SIDE. K4=0 IF NEITHER IS TRUE. LOUTF=1 IF THE
C FACET FACES AWAY FROM THE PRIMARY POINT OR TOUCH POINT AND
C LOUTF=-1 IF IT FACES TOWARD THE POINT. PDIST IS THE
C DISTANCE FROM THE TOUCH POINT OR PRIMARY POINT TO THE
C FACET SURFACE ALONG THE VECTOR.
C
        SUBROUTINE PIERC(KP,K1,K2,K3,K4,LOUTF,PDIST,ICW)
        DIMENSION RX(3),RY(3),RZ(3),PX(3),PY(3),PZ(3),KA(3)
        COMMON /DMABUF/IDUM(3700),M(100,3)
        COMMON /FACT/ IFMAX,NX(30),NA,IPS,NCON,NPOL
        COMMON /IPTPS/ IANG(100,2)
        DATA PI/3.1415927
        IF(ICW.NE.4)GOTO 40
C LINE SEGMENT MODE
        KA(1)=K2
        KA(2)=K3
        KA(3)=K4
C IGNORE COMPARISIONS IF ANY POINTS ARE THE SAME
        DO 41 IIS=1,3
        IF(KA(IIS).EQ.K1)RETURN
41      IF(KA(IIS).EQ.KP)RETURN
C FIND ANGLES SIMILAR TO TOUCH VECTORS
        RDX=M(K1,1)-M(KP,1)
        RDY=M(K1,2)-M(KP,2)
        RDZ=M(K1,3)-M(KP,3)
        PGAP=SQRT(RDX*RDX+RDY*RDY+RDZ*RDZ)
        PG=SQRT(RDX*RDX+RDY*RDY)
        IF(PG.NE.0)GOTO 42
        CTHET=1
        STHET=0
        GOTO 43
42      CTHET=RDX/PG
        STHET=RDY/PG
43      IF(PGAP.NE.0)GOTO 44
        CPHI=1
```

```
        SPHI=0
        GOTO 50
44      SPHI=RDZ/PGAP
        CPHI=PG/PGAP
        GOTO 50
C ORDINARY MODE
C KP IS POINT WITH TOUCH VECTOR
C K1,K2,K3 DESCRIBE THE FACET
40      IF(KP.EQ.K1.OR.KP.EQ.K2.OR.KP.EQ.K3)RETURN
        CTHET=COS(FLOAT(IANG(KP,1))*.0001)
        STHET=SIN(FLOAT(IANG(KP,1))*.0001)
        CPHI=COS(FLOAT(IANG(KP,2))*.0001)
        SPHI=SIN(FLOAT(IANG(KP,2))*.0001)
        KA(1)=K1
        KA(2)=K2
        KA(3)=K3
50      DO 30 J=1,3
        PX(J)=M(KA(J),1)
        PY(J)=M(KA(J),2)
        PZ(J)=M(KA(J),3)
C GET POINTS IN COORDINATES OF KP POINT AND
C TRANSFORM COORDINATES SUCH THAT THE VECTOR LAYS ON THE
C X AXIS
        RDX=PX(J)-M(KP,1)
        RDY=PY(J)-M(KP,2)
        RDZ=PZ(J)-M(KP,3)
        RX(J)=(CTHET*RDX+STHET*RDY)*CPHI+SPHI*RDZ
        RY(J)=-STHET*RDX+CTHET*RDY
        RZ(J)=-(CTHET*RDX+STHET*RDY)*SPHI+CPHI*RDZ
30      CONTINUE
C
C       CHECK PIERCING
C IF THE VECTOR PIERCES THE TRIANGLE, THE CORNER POINTS
C WILL SURROUND THE X AXIS
        IPIERC=0
        T1=ATAN2(RY(1),RZ(1))
        T2=ATAN2(RY(2),RZ(2))-T1
        T3=ATAN2(RY(3),RZ(3))-T1
        IF(T2.LT.0)T2=T2+2*PI
        IF(T3.LT.0)T3=T3+2*PI
C
C CHECK IF TOUCH VECTOR IS GREATER THAN 90 DEG FROM NORMAL
        IF(ICW.EQ.4)GOTO 55
C IF THE TWO OTHER POINTS GO SEQUENTIALLY CLOCKWISE WHEN
C LOOKING DOWN THE TOUCH VECTOR, THEN THE FACET IS MORE
C THAN 90 DEGREES AWAY
        ICW=0
        IF(T2.LT.PI)ICW=1     ! GREATER THAN 90 DEG
C
55      IF(T2.GT.PI)GOTO 32
        IF(T3.GT.PI.AND.T3.LT.T2+PI)IPIERC=1
        GOTO 36
```

```
3:        IF(T3.LT.PI.AND.T3.GT.T2-PI)IPIERC=1
36        CONTINUE
C
C CHECK IF FACET POINTS OUT OR IN
C     FIND CROSS PRODUCT OF FACET
          DO 408 I=2,3
          RX(I)=RX(I)-RX(1)
          RY(I)=RY(I)-RY(1)
408       RZ(I)=RZ(I)-RZ(1)
          QX=RY(2)*RZ(3)-RZ(2)*RY(3)
          QY=RZ(2)*RX(3)-RX(2)*RZ(3)
          QZ=RX(2)*RY(3)-RY(2)*RX(3)
C    D IS POSITIVE IF FACET POINTS AWAY
          D=(RX(1)*QX+RY(1)*QY+RZ(1)*QZ)
          PDIST=100000
          IF(QX.NE.0.0)PDIST=D/QX
C LOUTF=1 IF FACET FACES AWAY FROM POINT AND -1 OTHERWISE
          LOUTF=-1
          IF(D.LT.0)LOUTF=1
C PDIST IS DISTANCE ALONG TOUCH VECTOR TO FACET SURFACE
          IF(PDIST.LT.0)IPIERC=-IPIERC
          IF(ICW.NE.4)K4=IPIERC
          IF(ICW.NE.4.OR.IPIERC.EQ.0)RETURN
C INDICATE THAT SEGMENT PIERCES FACET
          IF(PDIST.GT.0.AND.PDIST.LT.PGAP)ICW=6
          RETURN
          END
          SUBROUTINE CROSS(M1,M2,M3,I)
C THIS SUBROUTINE FINDS THE SURFACE NORMAL OF A FACET
          COMMON /DMABUF/IDUM(3700),M(100,3)
          COMMON /TVEC/ TX(8),TY(8),TZ(8)
          A1=M(M2,1)-M(M1,1)
          A2=M(M2,2)-M(M1,2)
          A3=M(M2,3)-M(M1,3)
          B1=M(M3,1)-M(M1,1)
          B2=M(M3,2)-M(M1,2)
          B3=M(M3,3)-M(M1,3)
          TX(I)=A2*B3-A3*B2
          TY(I)=A3*B1-A1*B3
          TZ(I)=A1*B2-A2*B1
          RETURN
          END
C
          SUBROUTINE ANGL(I,J,A)
C THIS SUBROUTINE FINDS THE ANGLE BETWEEN TWO VECTORS
          COMMON /TVEC/TX(8),TY(8),TZ(8)
          R=TX(I)*TX(J)+TY(I)*TY(J)+TZ(I)*TZ(J)
          S1=SQRT((TX(I)*TX(I)+TY(I)*TY(I)+TZ(I)*TZ(I)))
          S2=SQRT((TX(J)*TX(J)+TY(J)*TY(J)+TZ(J)*TZ(J)))
          B=R/(S1*S2)
          IF(ABS(B).GT.1)TYPE *,'ERROR IN ANGL'
          B=ABS(ACOS(B))
```

```
      A=A+B
      RETURN
      END
C
      SUBROUTINE SEARCH(N1,N2,N3,N4)
C THIS SUBROUTINE FINDS THE 3RD POINT OF A FACET GIVEN THE
C OTHER TWO IN SEQUENCE. IT ALSO RETURNS THE FACET NUMBER.
      COMMON /DMABUF/ IDUM(3100),IFC(200,3)
      COMMON /FACT/ IFMAX,NX(30),NA,IPS
      N3=0
      DO 10 I=1,IFMAX
      J=0
      IF(N1.EQ.IFC(I,1))J=1
      IF(N1.EQ.IFC(I,2))J=2
      IF(N1.EQ.IFC(I,3))J=3
      IF(J.EQ.0)GOTO 10
      IF(N2.NE.IFC(I,1+MOD(J,3)))GOTO 10
      N3=IFC(I,1+MOD(J+1,3))
      N4=I
      RETURN
10    CONTINUE
      RETURN
      END
C
      SUBROUTINE VECT(I1,I2)
C THIS SUBROUTINE DRAWS A LINE BETWEEN TWO TOUCH POINTS
      COMMON /DMABUF/IDUM(3700),M(100,3)
10    CALL MOVI3(M(I1,1),M(I1,2),M(I1,3))
      CALL DRWI3(M(I2,1),M(I2,2),M(I2,3))
      RETURN
      END
```

```
      SUBROUTINE DISP
      DIMENSION T(7),DT(7)
      BYTE IBUF(3)
      COMMON /DMABUF/ IDUM(3100),IFC(200,3),M(100,3)
      COMMON /IPTPS/ IANG(100,2),ICHECK,VEX,IFCC
      COMMON /PAST/ IFMAX,NX(50),NA,NT,NCON,NPOL,ICCN,
     1 IVECT,ISUB,IRX
      COMMON /DISPL/ICM,XXD,XYD,XZD,XTD,YXD,YYD,YZD,YTD,
     1 ZXD,ZYD,ZZD,ISHAD,IARM,IWALL,IROLL,JSTICK,IDOTR
      DATA INTPN,INWALL,INARM /13,13,13/
C DRAW INSTRUCTIONS
      IF(ICM.EQ."113.OR.IRX.EQ.-5)GOTO 208
      IRX=0
      IQS=0
      IF(ICM.NE."117)GOTO 733
C INITIATE JOYSTICK ROTATIONS
      IQS=1
      IF(JSTICK.EQ.0)JSTICK=-1        ! JOYSTICK FLAG
      JSTICK=-JSTICK
      IF(JSTICK.NE.1)IROLL=0
733   IF(JSTICK.NE.1)GOTO 300
      IROLL=1
      CALL JROL(TX,TY,TZ,IQS)
      IF(IQS.EQ.-1)JSTICK=-JSTICK
      IF(JSTICK.NE.1)IROLL=0
300   IF(ICM.NE."125)GOTO 301
C INITIATE SCREEN OSCILLATIONS
      TYPE *,'INPUT CYCLES/SEC AND MAX ANGLE'
      ACCEPT *,PER,OSC
      OSC=OSC/360.
      PER=PER*6.283
      TOS=SECNDS(0.0)
      IROLL=1
C CHECK TWO KEY COMMAND CONDITION FLAG
301   IF(ICM.NE.0.AND.IPCON.EQ.1)GOTO 700
      IF(ICM.NE.0.AND.IPCON.EQ.2)GOTO 800
      IF(ICM.EQ."120)IPCON=2
      IF(ICM.EQ."131)IPCON=1
      IF(JSTICK.EQ.1)RETURN
      IF(ICM.EQ."131.OR.ICM.EQ."120)RETURN
      IF(ICM.EQ."040)GOTO 400    ! STOP ROTATIONS
      IF(IROLL.EQ.1)GOTO 200     ! SKIP FOR ROTATIONS
      IF(ICM.EQ."132)STOP
      IF(ICM.EQ."123)IRX=-1      ! REDRAW DISPLAY
      IF(ICM.NE."115)GOTO 458    ! SET INTENSITY OF MANIP
      INARM=MOD(1+INARM,16)
      CALL MODIFY(IARM)
      CALL SETINT(INARM)
458   IF(ICM.NE."127)GOTO 459    ! SET INTENSITY OF WALLS
      INWALL=MOD(1+INWALL,16)
      CALL MODIFY(IWALL)
```

```
        CALL SETINT(INWALL)
459     IF(ICM.NE."111)GOTO 461    ! SET INTENSITY OF POINTS
        INTPNT=MOD(1+INTPNT,16)
        CALL MODIFY(NCON-1)
        CALL SETINT(INTPNT)
461     IF(ICM.EQ."122)IRX=-2      ! INITIALIZE PROGRAM
        IF(ICM.EQ."110)IRX=-4      ! STOP QIO
        IF(IRX.LT.0)RETURN
602     IF(ICM.NE."067)GOTO 603    ! SET TOP VIEW
        VP1=0
        VP2=-.75
        VP3=0
603     IF(ICM.NE."061)GOTO 604    ! SET FRONT VIEW
        VP1=-.75
        VP2=0
        VP3=0
604     IF(ICM.NE."060)GOTO 605    ! CENTER PICTURE
        TX=0
        TY=0
        TZ=0
605     IF(ICM.NE."065)GOTO 200    ! SET SIDE VIEW
        VP1=.5
        VP2=0
        VP3=0
200     IF(ICM.NE."114)GOTO 618    ! SET NORMAL VIEW
        VP1=-.55
        VP2=.04
        VP3=0.
        S=1.
618     IF(ICM.EQ."070)DT(1)=.0008    ! SET ROTATION SPEEDS
        IF(ICM.EQ."062)DT(1)=-.0008
        IF(ICM.EQ."064)DT(2)=.0008
        IF(ICM.EQ."066)DT(2)=-.0008
        IF(ICM.EQ."105)DT(6)=.0008
        IF(ICM.EQ."124)DT(6)=-.0008
        IF(ICM.EQ."075)DT(3)=10.
        IF(ICM.EQ."047)DT(3)=-10.
        IF(ICM.EQ."133)DT(4)=10.
        IF(ICM.EQ."134)DT(4)=-10.
        IF(ICM.EQ."073)DT(7)=10.
        IF(ICM.EQ."173)DT(7)=-10.
        IF(ICM.EQ."071)DT(5)=.004
        IF(ICM.EQ."063)DT(5)=-.004
        DO 450 I=1,7
450     IF(ABS(DT(I)).GT..00001)IROLL=1
        J=0
        DO 451 I=1,7
        T(I)=T(I)+DT(I)
451     IF(T(I).NE.0)J=J+1
        IF(J.EQ.0.AND.PER.EQ.0.)IROLL=0
460     VP3=VP3+T(6)
        VP2=VP2+T(1)
```

```
        VP1=VP1+T(2)
        TOS=SECNDS(TOS1)
        TOS1=TOS1+TOS
        T.S=MOD(TOS1*PER,6.283)
        VP2=VP1+OSC*SIN(TOS)
        TY=TY+T(3)/S
        TX=TX+T(4)/S
        TZ=TZ+T(7)/S
        S=S*(1.-T(5))
        IF(S.GT.10.)S=15.9
        DO 452 I=1,7
452     DT(I)=0
        ICM=0
201     SP1=SIN(VP1*6.28)
        SP2=SIN(VP2*6.28)
        CP1=COS(VP1*6.28)
        CP2=COS(VP2*6.28)
        CP3=COS(VP3*6.28)
        SP3=SIN(VP3*6.28)
C CALCULATE SCREEN TRANSFORMATIONS
        XXD=CP1*CP3*S
        XYD=CP1*SP3*S
        XZD=-SP1*S
        XTD=(TX*XXD+TY*XYD+TZ*XZD)
        YXD=(-CP2*SP3+SP2*SP1*CP3)*S
        YYD=(CP2*CP3+SP2*SP1*SP3)*S
        YZD=SP2*CP1*S
        YTD=(TX*YXD+TY*YYD+TZ*YZD)
        ZXD=(SP2*SP3+CP2*SP1*CP3)*S
        ZYD=(-SP2*CP3+CP2*SP1*SP3)*S
        ZZD=CP2*CP1*S
        RETURN
400     DO 401 I=1,7
401     T(I)=0
        RETURN
C  INITIATE POLYHEDRON CONSTRUCTION
700     IF(ICM.NE."107)GOTO 701
        CALL LETTRO(NCON)
        IFMAX=0
        ICON=1
        IPS=0
        DO 121 J=1,3
        DO 121 I=1,100
        M(I,J)=0
        IFC(I,J)=0
        IFC(I*2,J)=0
        IF(J.EQ.3)GOTO 121
        IANG(I,J)=0
121     CONTINUE
701     IF(ICM.NE."122)GOTO 703    ! RESTART POLYHEDRON
        I=IPST
        ICON=1
```

```
703     IF(ICM.NE."127)GOTO 704    ! REDRAW WALLS
        DO 705 I=1,IFMAX
779     DO 705 J=1,3
        IF(IFC(I,J).GT.IFC(I,1+MOD(J,3)))GOTO 705
        CALL VECT(IFC(I,J),IFC(I,1+MOD(J,3)))
705     CALL MGSEND
704     IF(ICM.NE."101)GOTO 70! CONNECT POINTS ALREADY READ
        CALL LDPTRO(NCON)
        ICCN=1
        DO 777 I=1,IFMAX
        DO 777 J=1,3
777     IFC(I,J)=0
        IFMAX=0
        IPST=IPS
        DO 707 I=1,IPST
        IPS=I
707     CALL CON
706     IF(ICM.NE."124)GOTO 708  ! DRAW TOUCH VECTORS
        DO 709 I=1,IPS
        CALL MOVI3(M(I,1),M(I,2),M(I,3))
        CTHET=COS(FLOAT(IANG(I,1))*.0001)
        STHET=SIN(FLOAT(IANG(I,1))*.0001)
        CPHI=COS(FLOAT(IANG(I,2))*.0001)
        SPHI=SIN(FLOAT(IANG(I,2))*.0001)
        MXX=100.*CTHET*CPHI+M(I,1)
        MYY=100.*STHET*CPHI+M(I,2)
        MZZ=100.*SPHI+M(I,3)
709     CALL DRWI3(MXX,MYY,MZZ)
        CALL MGSEND
C DRAW CONTOURS
708     IF(ICM.NE."103.AND.ICM.NE."110)GOTO 781
        MYY=50
        IF(ICM.EQ."103)GOTO 710
        WRITE(5,783)
783     FORMAT(' INPUT NUMBER OF SECTIONS')
        READ(5,*)MYY
782     CALL CTOUR(MYY)
710     IF(ICM.NE."120)GOTO 711  ! CHECK IF FACETS FOLD
        ICW5=0
        DO 713 I=1,IFMAX
        DO 713 J=1,IFMAX
        DO 713 K=1,3
        MYY=IFC(J,K)
        MZZ=IFC(J,1+MOD(K,3))
        IF(MYY.GE.MZZ)GOTO 713
        MXX=4
        CALL PIERC(MYY,MZZ,I,I,CP1,CP2,SP1,MXX)
        IF(MXX.NE.6)GOTO 713
        ICW5=ICW5+1
        WRITE(5,714)MYY,MZZ,IFC(I,1),IFC(I,2),IFC(I,3)
714     FORMAT(' LINE',I4,' TO',I4,' PIERCES FACET',3I4)
713     CONTINUE
```

```
711     IF(ICM.NE."106)GOTO 715  ! R CHECK FACETS
        MZZ=0                    ! FOR SMOOTHNESS
        DO 716 I=1,IFMAX
        DO 433 J=1,3
        MXX=IFC(I,J)
        MYY=IFC(I,1+MOD(J,3))
        IF(MXX.GE.[illegible])GOTO 433
        IF(IFC.EQ.1)MZZ=MZZ+1
        CALL FAC(MXX,MYY)
433     CONTINUE
716     CONTINUE
        WRITE(5,12)MZZ
12      FORMAT('   OF FACET CHANGES=',I6)
715     IF(ICM.NE."116)GOTO 717     ! DRAW POINT NUMBERS
        DO 719 I=1,IPS
        CALL MOVI3(M(I,1),M(I,2),M(I,3))
        ENCODE(3,718,IBUF)I
        CALL CHAR(IBUF,3,1,0)
718     FORMAT(I3)
        CALL MGSEND
719     CONTINUE
717     IF(ICM.NE."114)GOTO 725  ! LOOK AT FACET PAIR DATA
        WRITE(5,729)
        READ(5,*)K1,K2
        ICHECK=1
        CALL FACE(K1,K2)
        ICHECK=0
725     IF(ICM.NE."111)GOTO 726
        ICHECK=2
        WRITE(5,729)
729     FORMAT(' INPUT K1 AND K2')
        READ(5,*)K1,K2
        CALL FACE(K1,K2)
        ICHECK=0
726     IF(ICM.NE."115)GOTO 727  ! GET COORDS OF A POINT
        WRITE(5,728)             ! AND ITS TOUCH VECTOR
728     FORMAT(' INPUT POINT  ')
        READ(5,*)I
        WRITE(5,*)M(I,1),M(I,2),M(I,3)
        CTHET=COS(FLOAT(IANG(I,1))*.0001)
        STHET=SIN(FLOAT(IANG(I,1))*.0001)
        CPHI=COS(FLOAT(IANG(I,2))*.0001)
        SPHI=SIN(FLOAT(IANG(I,2))*.0001)
        MXX=100.*CTHET*CPHI+M(I,1)
        MYY=100.*STHET*CPHI+M(I,2)
        MZZ=100.*SPHI+M(I,3)
        WRITE(5,*)MXX,MYY,MZZ
727     IF(ICM.NE."112)GOTO 735  ! WRITE ALL FACET DATA
        DO 731 I=1,IFMAX
        WRITE(5,*)IFC(I,1),IFC(I,2),IFC(I,3)
731     CONTINUE
735     IF(ICM.NE."130)GOTO 736 ! CHECK IF ANY TOUCH VECTORS
```

```
      DO 737 I=1,IFMAX          ! PIERCE THE POLYHEDRON
      DO 738 J=1,IPS
      MXX=0
      IF(J.EQ.IFC(I,1).OR.J.EQ.IFC(I,2).OR.J.EQ.IFC(I,
     1 3))GOTO 738
      CALL PIERC(J,IFC(I,1),IFC(I,2),IFC(I,3),CP1,CP2,
     1 SP1,MXX)
      IF(CP1.EQ.0.OR.SP1.LE.0)GOTO 738
      CP2=SP1/40.
      WRITE(5,739)J,IFC(I,1),IFC(I,2),IFC(I,3),CP2
739   FORMAT(' VECTOR',I4,' PIERCES FACET',3I4,'  AT',
     1 F9.4,' INCHES')
738   CONTINUE
737   CONTINUE
736   IPCON=0
      RETURN
800   IF(ICM.NE."104)GOTO 802      ! DRAW POINTS
      DO 803 I=1,IPS
803   CALL PNTI3(M(I,1),M(I,2),M(I,3))
      CALL MGSEND
802   IF(ICM.NE."112)GOTO 804      ! DELETE POINT
      TYPE *,'INPUT NUMBER OF POINT TO DELETE,0=END'
      ACCEPT *,MEND
      IF(MEND.EQ.0.OR.MEND.GT.IPS)RETURN
      DO 805 I=MEND,IPS
      M(I,1)=M(I+1,1)
      M(I,2)=M(I+1,2)
      M(I,3)=M(I+1,3)
      IANG(I,1)=IANG(I+1,1)
805   IANG(I,2)=IANG(I+1,2)
      IFMAX=0
      IPS=IPS-1
      DO 806 I=1,200
      IFC(I,1)=0
      IFC(I,2)=0
806   IFC(I,3)=0
804   IF(ICM.NE."103)GOTO 807    ! CLEAR ALL POINTS
      DO 808 I=1,100
      DO 808 J=1,3
      M(I,J)=0
      IFC(I,J)=0
      IFC(I+100,J)=0
      IF(J.EQ.3)GOTO 808
      IANG(I,J)=0
808   CONTINUE
      ICCN=0
      IPS=0
      IFMAX=0
807   IF(ICM.EQ."113)ICCN=0 !STOP POINT CONNECTIONS
      IF(ICM.NE."114)GOTO 809 !WRITE DATA TO FILE
      TYPE *,'FOR LEXIDATA "1" FOR MEGATEK "2"'
      ACCEPT *,IWRT
```

```
      IF(IWRT.EQ.1)OPEN(UNIT=1,NAME='LEX.DAT',TYPE='NEW')
      IF(IWRT.EQ.2)OPEN(UNIT=1,NAME='MEG.DAT',TYPE='NEW')
      WRITE(1,*)IPS,IFMAX
      DO 810 I=1,IPS
      MXX=M(I,1)*XXD+M(I,2)*XYD+M(I,3)*XZD+XTD
      MYY=M(I,1)*YXD+M(I,2)*YYD+M(I,3)*YZD+YTD
      MZZ=M(I,1)*ZXD+M(I,2)*ZYD+M(I,3)*ZZD
      IF(IWRT.EQ.2)WRITE(1,*)M(I,1),M(I,2),M(I,3)
810   IF(IWRT.EQ.1)WRITE(1,*)MXX,MYY,MZZ
      DO 811 I=1,IFMAX
811   WRITE(1,*)IFC(I,1),IFC(I,2),IFC(I,3),
     1  IANG(I,1),IANG(I,2)
      CLOSE(UNIT=1,DISPOSE='SAVE')
809   IF(ICM.NE."122)GOTO 815 ! READ DATA FROM FILE
      OPEN(UNIT=1,NAME='MEG.DAT',TYPE='OLD')
      READ(1,*)IPS,IFMAX
      DO 814 I=1,IPS
814   READ(1,*)M(I,1),M(I,2),M(I,3),IANG(I,1),IANG(I,2)
      DO 813 I=1,IFMAX
813   READ(1,*)IFC(I,1),IFC(I,2),IFC(I,3)
      CLOSE(UNIT=1,DISPOSE='SAVE')
815   IF(ICM.NE."116)GOTO 818 !  ARRANGE TO WRITE LARGE
      IF(IDOTR.EQ.1)GOTO 819  ! LARGE NUMBER OF POINTS
      OPEN(UNIT=2,NAME='DOT.DAT',TYPE='NEW')
      IDOTR=1
      GOTO 818
819   CLOSE(UNIT=2,DISPOSE='SAVE')
      IDOTR=0
818   IF(ICM.NE."115)GOTO 820! READ MORE THAN 100 POINTS
      OPEN(UNIT=2,NAME='DOT.DAT',TYPE='OLD')
      DO 822 I=1,8000
      READ(2,*,END=821)MMX,MMY,MMZ
      CALL PNTI3(MMX,MMY,MMZ)
822   CALL MGSEND
821   CLOSE(UNIT=2,DISPOSE='SAVE')
      TYPE *,I
820   IPCON=0
      RETURN
C PRINT DISPLAY CONTROL INSTRUCTIONS
208   TYPE *,' TO ROTATE TYPE:'
      TYPE *,' 3=UP  2=DOWN  6=RIGHT  4=LEFT  5=FRONT ',
     1  '1=SIDE  7=TOP'
      TYPE *,'  L=ORIENTED VIEW   E=CW  T=CCW'
      TYPE *,' TO TRANSLATE TYPE:'
      TYPE *,' "="=UP,"=DOWN,[=RIGHT,=LEFT,0=CENTER,; ',
     1  '=FOWARD,{=BACK'
      TYPE *,' 9=ZOOM UP  3=ZOOM DOWN, TYPE "M"',
     1  'FOR MANIPULATOR'
      TYPE *,' TYPE "S" TO ERASE, "W" FOR WALLS, I FOR ',
     1  ' POINT INT'
      TYPE *,' TYPE "Z" TO EXIT, "R" TO REPEAT, "K" FOR ',
     1  'INSTRUCTIONS'
```

```
      TYPE *,' TYPE  "H" TO HALT KEYBOARD ROTATIONS'
      TYPE *,' C'
      TYPE *,' "P"   FOR POINT MANIPULATION -- THEN TYPE'
      TYPE *,'  N= READ POINTS TO DOT.  R=RECALL POINT ',
     1 'AND LINE DATA'
      TYPE *,' TYPE D=DRAW POINTS J=DELETE SPECIFIC POINT'
      TYPE *,' C=CLEAR EVERYTHING, K=DOT ENABLE, L=SAVE ',
     1 'FOR LEX OR MEG'
      TYPE *,' C'
      TYPE *,' FOR POINT CONNECTIONS -- FIRST TYPE ',
     1 '"Y" THEN- '
      TYPE *,' G=START, S=START WITH SURFACE, B=SUPPRESS',
     1 ' BASE POINTS'
      TYPE *,' E=END, R=RESUME, W=REDRAW, T=TOUCH ',
     1 'VECTORS, C=50 CONTOUR'
      TYPE *,' SECTIONS, H=CONTOUR SECTIONS, A=CONNECT ',
     1 'POINTS ALREADY READ'
      TYPE *,' V=CHANGE CONCAVITY FACTOR  X=CHECK TOUCH ',
     1 'VECTOR PIERCING'
      TYPE *,' P=CHECK LINE PIERCING OF FACETS  F=CHECK',
     1 ' ALL FACETS'
      TYPE *,' I=CHANGE FACETS,L=LOOK AT FACETS,N=',
     1 'NUMBER FACETS'
      TYPE *,' M=COORDS OF POINT  J=FACET NUMBERS'
      TYPE *,' O=JOYSTICK OR TRACKBALL'
      IRX=0
      RETURN
      END
      SUBROUTINE CTOUR(IS)
C THIS SUBROUTINE DRAWS CONTOURS AROUND THE POLYHEDROM
C IN THE X-Y PLANE
C (IS) IS THE NUMBER OF CONTOURS
      DIMENSION NF(4)
      COMMON /DMABUF/ IDUM(3100),IFC(200,3),M(100,3)
      COMMON /IPTPS/ IANG(100,2)
      COMMON /FACT/ IFMAX,NX(30),NA,IPS,NCON,NPOL,ICCN,
     1 IVECT,ISUP,IRX
      COMMON /DISPL/ ICM,XXD,XYD,XZD,XTD,YXD,YYD,YZD,
     1 YTD,ZXD,ZYD,ZZD,ISHAD,IARM,IWALL,IROLL
      MAXZ=-2000
      MINZ=2000
C FIND THE MAX AND MIN Z VALUES OF THE POLYHEDRON
      DO 10 I=1,IPS
      IF(M(I,3).GT.MAXZ)MAXZ=M(I,3)
10    IF(M(I,3).LT.MINZ)MINZ=M(I,3)
      S=FLOAT(MAXZ-MINZ)/FLOAT(IS+1)
        DO 20 I=1,IS
        IZ=MAXZ-I*S   ! IZ IS THE GAP BETWEEN CONTOURS
          DO 30 J=1,IFMAX
C SEE IF FACET LAYS ACROSS THE CONTOUR IN QUESTION
432         DO 40 K=1,3
      IF(M(IFC(J,K),3).GE.IZ.AND.M(IFC(J,1+MOD(K,3)),
```

```
     1  3).LE.IZ)GOTO 50
40           CONTINUE
             GOTO 30
50           NF(1)=IFC(J,1)
             NF(2)=IFC(J,2)
             NF(3)=IFC(J,3)
             NF(4)=IFC(J,1
             D=FLOAT((IZ-M(NF(K),3))/FLOAT((M(NF(K),
     1       3)-M(NF(K+1),3)))
             IY1=  (M(NF(K),2)-M(NF(K+1),2))+M(NF(K),2)
             IX1=D*(M(NF(K),1)-M(NF(K+1),1))+M(NF(K),1)
             CALL MOVI3(IX1,IY1,IZ)
45           DO 70 K=1
          IF(M(NF(K),3).LE.IZ.AND.M(NF(K+1),3).GE.IZ)GOTO 80
             GOTO 70
80           D=FLOAT((IZ-M(NF(K),3)))/FLOAT((M(NF(K),
      1      3)-M(NF(K+1),3)))
90           IY2=D*(M(NF(K),2)-M(NF(K+1),2))+M(NF(K),2)
             IX2=D*(M(NF(K),1)-M(NF(K+1),1))+M(NF(K),1)
             IF(IY1.EQ.-1900.AND.IY2.EQ.-1900)GOTO 70
             CALL DRWI3(IX2,IY2,IZ)
70           CONTINUE
30           CONTINUE
             CALL MGSEND
20         CONTINUE
           RETURN
           END
```

APPENDIX E. PROGRAM FOR RASTER DISPLAY OF POLYHEDRON

```
      PROGRAM DRW
C THIS PROGRAM DRAWS A SHADED PICTURE OF A POLYHEDRON
C GIVEN THE 3-D COODINATES OF ALL ITS POINTS AND ITS
C CONNECTIVITY DATA
      DIMENSION NF(4),M(100,3),IFC(200,3),NN(200,2)
      DIMENSION R1(3),R2(3),IY(3)
      INTEGER BUFF1(200),BUFF2(200),BUFF3(200)
      DATA MM1,MM2,MM3/255,255,255/
C INITIALIZE DISPLAY
      CALL DSOPN(2,IE)
      CALL DSCSL(2,0,0)
      CALL DSCER
      CALL DSCLR(4095)
      I5=1
      PI=3.1415
C READ DATA FILE
      OPEN(UNIT=4,NAME='DL1:[200,214]0.DAT',TYPE ='OLD')
      READ(4,*)IPS,IFMAX
      DO 400 I=1,IPS
400   READ(4,*)M(I,1),M(I,2),M(I,3)
      DO 401 I=1,IFMAX
401   READ(4,*)IFC(I,1),IFC(I,3),IFC(I,2)
      CLOSE(UNIT=4,DISPOSE='SAVE')
      IFM=IFMAX
C REJECT ALL FACETS THAT FACE AWAY
      DO 402 M4=1,IFM
      I=IFM-M4+1
      IF(IFC(I,1).EQ.0)GOTO 402
      DO 403 J=1,3
      R1(J)=M(IFC(I,2),J)-M(IFC(I,1),J)
403   R2(J)=M(IFC(I,3),J)-M(IFC(I,1),J)
      QZ=R1(1)*R2(2)-R1(2)*R2(1)
      IF(QZ.LT.0)GOTO 402
      IFMAX=IFMAX-1
      DO 435 J=I,IFM
      DO 435 K=1,3
      IFC(J,K)=IFC(J+1,K)
435   CONTINUE
402   CONTINUE
C ORDER FACETS SO NEAREST ARE DRAWN LAST
      DO 405 J=1,IFMAX
      DO 406 I=1,IFMAX-1
      IF(IFC(I,1).EQ.0)GOTO 406
      M1=MAXO(M(IFC(I,1),3),M(IFC(I,2),3),M(IFC(I,3),3))
      M2=MAXO(M(IFC(I+1,1),3),M(IFC(I+1,2),3),
     1  M(IFC(I+1,3),3))
      IF(M1.GT.M2)GOTO 406
407   DO 408 K=1,3
      N=IFC(I,K)
      IFC(I,K)=IFC(I+1,K)
408   IFC(I+1,K)=N
```

```
406     CONTINUE
405     CONTINUE
C DRAW FACETS AS 2 DIMENSIONAL TRIANGLES ON SCREEN
        DO 409 I=1,IPS
        NN(I,1)=M(I,1)*4/25+320
409     NN(I,2)=-M(I,2)*4/25+256
        DO 410 I=1,IFMAX
        DO 413 J=1,3
413     IY(J)=J
        DO 411 J=1,3
        DO 412 K=1,2
        IF(NN(IFC(I,IY(K)),2).LE.NN(IFC(I,IY(K+1)),
     1  2))GOTO 412
        N=IY(K)
        IY(K)=IY(K+1)
        IY(K+1)=N
412     CONTINUE
411     CONTINUE
        IYT=NN(IFC(I,IY(1)),2)
        IYM=NN(IFC(I,IY(2)),2)
        IYB=NN(IFC(I,IY(3)),2)
        IXT=NN(IFC(I,IY(1)),1)
        IXM=NN(IFC(I,IY(2)),1)
        IXB=NN(IFC(I,IY(3)),1)
        IF(IYB.EQ.IYT)GOTO 410
        IF(IYM.EQ.IYT)GOTO 441
        F=FLOAT(IYM-IYT)/FLOAT(IYB-IYT)
440     IX2M=IXT+FLOAT(IXB-IXT)*F
        IF(IYB.LT.1)GOTO 410
        IF(IYT.GT.512)GOTO 410
        DO 414 J=IYT,IYM
        F=FLOAT(J-IYT)/FLOAT(IYM-IYT)
        IX1=IXT+FLOAT(IXM-IXT)*F
        IX2=IXT+FLOAT(IX2M-IXT)*F
        CALL TRI(IX1,IX2,J,I)
414     CONTINUE
441     IF(IYB.EQ.IYM)GOTO 410
        DO 415 J=IYM,IYB
        F=FLOAT(J-IYM)/FLOAT(IYB-IYM)
        IX1=IXM+FLOAT(IXB-IXM)*F
        IX2=IX2M+FLOAT(IXB-IX2M)*F
        CALL TRI(IX1,IX2,J,I)
415     CONTINUE
410     CONTINUE
C READ DATA FROM TRACKBALL
1       CALL TBALL(IXX,IYY,IZ)
        IF(IXX.EQ.0.AND.IYY.EQ.0.AND.IZ.EQ.0)GOTO 1
        IAX=IAX+IXX*TS
        IAY=IAY+IYY*TS
        IF(IZ.EQ.1)GOTO 1
        IF(IZ.EQ.0)GOTO 436
        IF(IZ.EQ.IZ2)GOTO 1
```

```
      IF(IZ.NE.3)GOTO 437
      TYPE *,'INPUT BACKGROUND BLUE-GREEN-RED SHADES,
     1  0-255'
      ACCEPT *,M1,M2,M3
      CALL DSLLU(1024,M1,1024,M1)
      CALL DSLLU(2048,M2,2048,M2)
      CALL DSLLU(3072,M3,3072,M3)
437   IF(IZ.NE.6)GOTO 438
      TYPE *,'INPUT OBJECT BLUE-GREEN-RED SHADES,0-255'
      ACCEPT *,MM1,MM2,MM3
438   IF(IZ.EQ.7)CALL EXIT
C CALCULATE SHADES FOR ALL TRIANGLES
436   AX=FLOAT(IAX)*PI/180.
      AY=FLOAT(IAY)*PI/180.
      IZ2=IZ
      SX=SIN(AX)
      SY=COS(AX)*SIN(AY)
      SZ=-COS(AX)*COS(AY)
      DO 422 I=1,IFMAX
      IF(IFC(I,1).EQ.0)GOTO 422
      DO 423 J=1,3
      R1(J)=M(IFC(I,2),J)-M(IFC(I,1),J)
423   R2(J)=M(IFC(I,3),J)-M(IFC(I,1),J)
      QX=R1(2)*R2(3)-R1(3)*R2(2)
      QY=R1(3)*R2(1)-R1(1)*R2(3)
      QZ=R1(1)*R2(2)-R1(2)*R2(1)
      DLEN=SQRT(QX*QX+QY*QY+QZ*QZ)
      DENS=(QX*SX+QY*SY+QZ*SZ)/DLEN
      IF(DENS.LT.0)DENS=0
      BUFF1(I)=DENS*FLOAT(MM1)
      BUFF2(I)=DENS*FLOAT(MM2)
      BUFF3(I)=DENS*FLOAT(MM3)
422   CONTINUE
C SEND SHADES TO DISPLAY
      CALL DSLWT(1025,IFMAX,BUFF1)
      CALL DSLWT(2049,IFMAX,BUFF2)
      CALL DSLWT(3073,IFMAX,BUFF3)
      GOTO 1
      END
      SUBROUTINE TRI(IX1,IX2,J,I)
C THIS SUBROUTINE DRAWS THE ACTUAL LINES ON THE SCREEN
      IF(J.GT.512)RETURN
      IF(J.LT.1)RETURN
      IF(IX1.GT.640)IX1=640
      IF(IX2.GT.640)IX2=640
      IF(IX1.LT.1)IX1=1
      IF(IX2.LT.1)IX2=1
      IF(ABS(IX1-IX2).LT.1)RETURN
      CALL DSVEC(IX1,J,IX2,J,I)
      RETURN
      END
```

DISTRIBUTION LIST

CDR Paul R. Chatelier
Office of the Deputy Under Secretary
of Defense
OUSDRE (E&LS)
Pentagon, Room 3D129
Washington, D.C. 20301

Director
Engineering Psychology Programs
Code 455
Office of Naval Research
800 North Quincy Street
Arlington, VA 22217 (5 cys)

Director
Aviation & Aerospace Technology
Code 210
Office of Naval Research
800 North Quincy Street
Arlington, VA 22217

Director
Undersea Technology
Code 220
Office of Naval Research
800 North Quincy Street
Arlington, VA 22217

Director
Communication & Computer Technology
Code 240
Office of Naval Research
800 North Quincy Street
Arlington, VA 22217

Director
Tactical Development & Evaluation
Support
Code 230
Office of Naval Research
800 North Quincy Street
Arlington, VA 22217

Director
Manpower, Personnel and Training
Code 270
Office of Naval Research
800 North Quincy Street
Arlington, VA 22217

Director
Information Systems Program
Code 437
Office of Naval Research
800 North Quincy Street
Arlington, VA 22217

Cdr. K. Hull
Code 410
Office of Naval Research
800 North Quincy Street
Arlington, VA 22217

Director
Physiology Program
Code 441
Office of Naval Research
800 North Quincy Street
Arlington, VA 22217

Special Assistant for Marine
Corps Matters
Code 100M
Office of Naval Research
800 North Quincy Street
Arlington, VA 22217

Commanding Officer
ONR Eastern/Central Regional Office
ATTN: Dr. J. Lester
Building 114, Section D
666 Summer Street
Boston, MA 02210

Commanding Officer
ONR Western Regional Office
ATTN: Mr. R. Lawson
1030 East Green Street
Pasadena, CA 91106

Director
Naval Research Laboratory
Technical Information Division
Code 2627
Washington, D.C. 20375 (6 cys)

Dr. Perry Alers
Code 8420
Naval Research Laboratory
Washington, D.C. 20375

Dr. Robert G. Smith
Office of the Chief of Naval
Operations, OP987H
Personnel Logistics Plans
Washington, D.C. 20350

CDR G. Worthington
Office of the Chief of Naval
Operations, OP-372G
Washington, D.C. 20350

Dr. W. Mehuron
Office of the Chief of Naval
Operations, OP 987
Washington, D.C. 20350

Dr. Andreas B. Rechnitzer
Office of the Chief of Naval
Operations, OP 952F
Naval Oceanography Division
Washington, D.C. 20350

Dr. Jerry C. Lamb
Combat Control Systems
Naval Underwater Systems Center
Newport, RI 02840

Naval Training Equipment Center
ATTN: Technical Library
Orlando, FL 32813

Dr. Gary Poock
Operations Research Department
Naval Postgraduate School
Monterey, CA 93940

Mr. H. Talkington
Ocean Engineering Department
Naval Ocean Systems Center
San Diego, CA 92152

Mr. Paul Heckman
Naval Ocean Systems Center
San Diego, CA 92152

Mr. Warren Lewis
Human Engineering Branch
Code 8231
Naval Ocean Systems Center
San Diego, CA 92152

Dr. Ross L. Pepper
Naval Ocean Systems Center
Hawaii Laboratory
P.O. Box 997
Kailua, HI 96734

Dr. A. L. Slafkosky
Scientific Advisor
Commandant of the Marine Corps
Code RD-1
Washington, D.C. 20380

Dr. Ross L. Pepper
Naval Ocean Systems Center
Hawaii Laboratory
P. O. Box 997
Kailua, HI 96734

Mr. David Smith
Naval Ocean Systems Center
Hawaii Laboratory
P. O. Box 997
Kailua, HI 96734

Mr. Arnold Rubinstein
Naval Material Command
NAVMAT 0722 - Rm. 508
800 North Quincy Street
Arlington, VA 22217

Mr. Glen Spalding
Naval Material Command
Ocean Engineering & Technology
MAT 07
Washington, DC 20360

Mr. Phillip Andrews
Naval Sea Systems Command
NAVSEA 0341
Washington, D.C. 20362

Commander
Naval Electronics Systems Command
Human Factors Engineering Branch
Code 4701
Washington, D.C. 20360

LCOL B. Hastings
Marine Corps Liaison Officer
Naval Coastal Systems Center
Panama City, FL 32407

Mr. Milon Essoglou
Naval Facilities Engineering Command
R&D Plans and Programs
Code 03T
Hoffman Building II
Alexandria, VA 22332

CDR Robert Biersner
Naval Medical R&D Command
Code 44
Naval Medical Center
Bethesda, MD 20014

Dr. Arthur Bachrach
Behavioral Sciences Department
Naval Medical Research Institute
Bethesda, MD 20014

CDR Thomas Berghage
Naval Health Research Center
San Diego, CA 92152

Dr. George Moeller
Human Factors Engineering Branch
Submarine Medical Research Lab
Naval Submarine Base
Groton, CT 06340

Dr. James McGrath, Code 302
Navy Personnel Research and
Development Center
San Diego, CA 92152

Navy Personnel Research and
Development Center
Planning & Appraisal
Code 04
San Diego, CA 92152

Navy Personnel Research and
Development Center
Performance Measurement &
Enhancement
Code 309
San Diego, CA 92152

CDR Norman Lane
Human Factors Engineering Division
Naval Air Development Center
Warminster, PA 18974

Human Factors Branch
Code 3152
Naval Weapons Center
China Lake, CA 93555

Human Factors Engineering Branch
Code 1226
Pacific Missile Test Center
Point Mugu, CA 93042

Mr. J. Williams
Department of Environmental
Sciences
U.S. Naval Academy
Annapolis, MD 21402

Dean of the Academic Departments
U.S. Naval Academy
Annapolis, MD 21402

Human Factor Engineering Branch
Naval Ship Research and Development
Center, Annapolis Division
Annapolis, MD 21402

Mr. John Quirk
Naval Coastal Systems Laboratory
Code 712
Panama City, FL 32401

CDR W. Moroney
Code 55MP
Naval Postgraduate School
Monterey, CA 93940

Mr. Merlin Malehorn
Office of the Chief of Naval
Operations (OP-115)
Washington, D.C. 20350

Dr. Joseph Zeidner
Technical Director
U.S. Army Research Institute
5001 Eisenhower Avenue
Alexandria, VA 22333

Director, Organizations and
Systems Research Laboratory
U.S. Army Research Institute
5001 Eisenhower Avenue
Alexandria, VA 22333

Technical Director
U.S. Army Human Engineering Labs
Aberdeen Proving Ground, MD 21005

U.S. Air Force Office of Scientific
Research
Life Sciences Directorate, NL
Bolling Air Force Base
Washington, D.C. 20332

Director, Human Factors Wing
Defence & Civil Institute of
Environmental Medicine
Post Office Box 2000
Downsview, Ontario M3M 3B9
CANADA

Defense Technical Information Center
Cameron Station, Bldg. 5
Alexandria, VA 22314 (12 cys)

Director, Cybernetics Technology
Office
Defense Advanced Research Projects
Agency
1400 Wilson Blvd
Arlington, VA 22209

Mr. John B. Gregory
Research Program Manager
Branch of Marine Oil & Gas Operations
US Geological Survey
Reston, VA 22092

Dr. M. Montemerlo
Human Factors & Simulation
Technology, RTE-6
NASA HQS
Washington, D.C. 20546

Dr. J. Miller
Florida Institute of Oceanography
University of South Florida
St. Petersburg, FL 33701

Dr. Robert R. Mackie
Human Factors Research, Inc.
5775 Dawson Avenue
Goleta, CA 93017

Dr. Jesse Orlansky
Institute for Defense Analyses
400 Army-Navy Drive
Arlington, VA 22202

Dr. Harry Snyder
Department of Industrial Engineering
Virginia Polytechnic Institute and
State University
Blacksburg, VA 24061

Dr. W. S. Vaughan
Oceanautics, Inc.
422 6th Street
Annapolis, MD 21403

Dr. Robert T. Hennessy
NAS - National Research Council
JH #819
2101 Constitution Ave., N.W.
Washington, DC 20418

Dr. A. Freedy
Perceptronics, Inc.
6271 Variel Avenue
Woodland, CA 91364

Dr. Robert Williges
Human Factors Laboratory
Virginia Polytechnical Institute
and State University
130 Whittemore Hall
Blacksburg, VA 24061

Dr. Alphonse Chapanis
Department of Psychology
The Johns Hopkins University
Charles and 34th Streets
Baltimore, MD 21218

Dr. James H. Howard, Jr.
Department of Psychology
Catholic University
Washington, D.C. 20064

Dr. Christopher Wickens
University of Illinois
Department of Psychology
Urbana, IL 61801

Dr. Babur M. Pulat
Department of Industrial Engineering
North Carolina A&T State University
Greensboro, NC 27411

Dr. Richard W. Pew
Information Sciences Division
Bolt Beranek & Newman, Inc.
50 Moulton Street
Cambridge, MA 02138

Dr. David J. Getty
Bolt Beranek & Newman, Inc.
50 Moulton Street
Cambridge, MA 02138

Dr. Douglas Towne
University of Southern California
Behavioral Technology Laboratory
3716 S. Hope Street
Los Angeles, CA 90007

Dr. Baruch Fischhoff
Decision Research
1201 Oak Street
Eugene, OR 97401

Dr. A. K. Bejczy
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91125

Dr. Stanley N. Roscoe
New Mexico State University
Box 5095
Las Cruces, NM 88003

Mr. Joseph G. Wohl
MITRE Corporation
Box 208
Bedford, MA 01730

Dr. Rex Brown
Decision Science Consortium
Suite 721
7700 Leesburg Pike
Falls Church, VA 22043

J. Courtney
Dept. of Electrical Engineering
Univ. of Texas at Austin
Austin, Texas 78712


FILMED
8-8